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Electro-Osmotic Pulse Technology for Control of Water Seepage in Various Civil Works Structures

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October 2006



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Final Report

Approved for public release; distribution is unlimited.

Prepared for U.S. Army Corps of Engineers
Washington, DC 20314-1000

Under Work Unit #0089LG

ABSTRACT: Electro-osmotic pulse (EOP) was evaluated in the laboratory to compare the electrokinetic forces developed by the EOP system to the hydraulic forces within 4-in.-thick concrete. Systems were installed in two Civil Works structures, the old lock house at Lock and Dam 7 at Dresbach, MN, and in a section of gallery at Lock 27 at Granite City, IL. Laboratory testing indicates that EOP is able to dry the walls of concrete Civil Works structures up to 30 ft of head through a 4-in.-thick slab of concrete, and that EOP can be used to dry the concrete in lock house basements and lock galleries. The plate cathodes mounted in the water on the lock walls are effective cathode placements. Probe cathodes are also effective embedded in the lock walls. The effectiveness of probe cathodes is based on the surface area and not the manufacturing techniques used.

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Conversion Factors

Units of measure used in this report can be converted to SI* units as follows:

Multiply	By	To Obtain
degrees (angle)	0.01745329	radians
feet	0.3048	meters
gallons (U.S. liquid)	0.003785412	cubic meters
inches	0.0254	meters
pounds (force) per square inch	0.006894757	megapascals
pounds (mass)	0.4535924	kilograms
square ft	0.09290304	square meters

* *Système International d'Unités* (International System of Measurement), i.e., the metric system.

Preface

This study was conducted for Headquarters, U.S. Army Corps of Engineers under the Civil Works Infrastructure Technologies Program 0089LG, “Novel Technologies for Water Seepage Control in Hydraulic Structures.” The technical monitor was Andy Wu, CECW-EE.

The work was performed by the Materials and Structures Branch (CF-M) of the Facilities Division (CF), Construction Engineering Research Laboratory (CERL). The CERL Project Manager was Vincent F. Hock. Part of this work was performed by Drytronic, Inc., LaCrosse, WI. Martin J. Savoie is Chief, CF-M, and L. Michael Golish is Chief, CF. The Technical Director of the Facilities Acquisition and Revitalization business area is William Goran, and the Director of CERL is Dr. Ilker R. Adiguzel.

CERL is an element of the Engineer Research and Development Center (ERDC), U.S. Army Corps of Engineers. The Commander and Executive Director of the ERDC is COL Richard B. Jenkins, and the Director is Dr. James R. Houston.

1 Introduction

Background

The U.S. Army Corps of Engineers owns and maintains a large array of buried and immersed concrete structures such as locks, dams, and hydroelectric plants. The harsh environments that these concrete structures exist in render them vulnerable to damaging processes such as cracking, spalling, and water seepage. (Statistically, cracking, spalling, and water seepage account for more than 75 percent of concrete degradation as reported in the Corps Periodic Inspection Program [U.S. Congress 2002].)

One possible harmful effect of these destructive processes is that they can lead to catastrophic structural failure of the concrete structure. If left unchecked, the processes of cracking and spalling, in parallel with water seepage and intrusion, can lead to the rapid propagation of cracks during periodic freeze-thaw cycles. Over time, this progression can lead to uncontrollable crack propagation throughout the structure and eventually to catastrophic structural failure.

Another harmful effect of these destructive processes is that water intrusion through the concrete can eventually lead to the corrosion and destruction of critical electrical and mechanical components. Water intrusion into critical electrical components can lead to short circuiting, operation stoppage, and overall system failure. Water intrusion into critical mechanical components can lead to corrosion, system damage, and mechanical failure. Because of these possible failure mechanisms, something must be done to control moisture intrusion in buried and immersed concrete structures.

The conventional approach to moisture control in buried and immersed concrete structures has been to redirect or block intruded water from critical electrical and mechanical components that are subject to corrosion degradation. The most popular of these conventional approaches is to inject epoxy into critical path cracks. However, standard epoxy materials tend to fail over time, some in as little as 2 or 3 years, due to shrinkage of the injected material or disbondment of the coating (because of moisture migration through the waterproofing membrane or coating). Consequently, the product's short life span makes the use of epoxy a

time consuming and high maintenance practice. Also, epoxy use can be costly, especially if excavating or retrofitting is required. The cost per lineal foot can vary from \$300 to \$900.

Even if epoxy were adequate for eliminating water intrusion through cracks, other uncontrollable events can also lead to water intrusion into critical areas. Volume change due to thermal gradients, clogging of tiles and drains, and sump pump failure can all lead to unacceptable moisture levels in critical electrical and mechanical components.

Beyond keeping moisture away from critical components in concrete structures, another consideration regarding water seepage is to control the relative humidity of indoor concrete facilities. Moisture seepage through the concrete can result in a relative humidity level of over 95 percent in control towers, crossover tunnels, vaults, and storage basements. These high levels of relative humidity can lead to the rapid corrosion and destruction of systems held within the facility.

Electro-osmotic pulse (EOP) is a novel seepage control technology that has shown success in non-civil works structures. Previous work (Hock et al. 1998) has shown that EOP technology can eliminate groundwater intrusion in concrete structures and circumvent the need for conventional negative-side waterproofing methods (excavation, tiling, coatings, epoxies, and membranes) applied to shallow below-grade concrete structures.

Congress is aware of the magnitude of the water seepage problem and the potential benefits of EOP technology to solve that problem. The Committee on Appropriations inserted the following language into a report in explanation of the bill making appropriations for energy and water development (U.S. Congress 2002):

“In addition, the Committee encourages the Corps of Engineers to fully investigate the use of electro-osmotic-pulse technologies at facilities where chronic water seepage and floods are problematic.”

The study reported here was undertaken to determine if EOP is also suitable for buried and immersed structures such as locks, dams, national monuments, concrete bunkers, concrete vaults, elevator shafts, operating galleries, and basements that are subjected to significantly larger hydraulic pressure heads.

Objectives

The overall objectives of this work unit were to:

- Determine if EOP technology could control water intrusion into critical electrical and mechanical components of buried and immersed concrete structures.
- Determine the threshold hydraulic head that EOP technology could draw water against to prevent the intrusion of moisture into buried and immersed concrete structures.
- Determine if EOP technology is suitable for moving water away from an exposed face to prevent the relative humidity of an enclosed structure from reaching to an unacceptably high level.

Approach

Literature was reviewed to investigate current moisture control methods. Laboratory experiments were conducted to examine the effectiveness of electro-osmotic transport in a standard Civil Works concrete mix, specifically to:

- Test the effectiveness of EOP technology against varying hydraulic pressure heads to help determine if a given site may be a potential candidate for the installation of EOP technology.
- Determine an upper boundary hydraulic pressure head against which current EOP technology is not satisfactorily effective.
- Determine how the system can be modified to operate more effectively under various site conditions.
- Determine the effectiveness of EOP technology when used in conjunction with a range of concrete that is typical to Civil Works structures.

Field tests were conducted on two lock structures on the Mississippi River.

Conclusions were drawn regarding the relative performance of EOP technology compared with traditional methods for control of water intrusion, and recommendations were made regarding the use of the technology for this purpose.

Mode of Technology Transfer

It is anticipated that the results of this research will be incorporated into Draft Corps of Engineers Guide Specifications and Engineer Instructions to help Corps district and installation personnel control water seepage in porous building

construction materials used below-grade in both new construction and renovation. Plans are also to publish the results of this work in professional and trade journals.

2 Laboratory Testing

Description of Electro-Osmosis

In 1809, F.F. Reuss originally described electro-osmosis (EO) in an experiment that showed that water could be forced to flow through a clay-water system when an external electric field was applied to the soil (Reuss 1809). Research has since shown that flow is initiated by the movement of cations (positively charged ions) present in the pore fluid of clay or similar porous medium such as concrete; the water surrounding the cations moves with them. EO can be used to arrest or cause the flow of water as well as the ions in it. EO has been used in civil engineering to dewater dredgings and other high-water content waste solids, consolidate clays, strengthen soft sensitive clays, and increase the capacity of pile foundations. It has also received significant attention in the past 5 years as a method to remove hazardous contaminants from groundwater or to arrest water flow.

EOP technology is a new application based on the old concept of electro-osmosis. It uses the forced movement of an aqueous solution that contains a net electric charge due to an applied external electric field. EOP technology dramatically and effectively extends the basic concept of EO to below-grade concrete structures and soil through the novel application of an asymmetric dual polarity pulse and innovative electrode materials.

The basic equation for movement of the pore solution in a capillary porous system, such as clay or concrete, contains several forces (Tikhomolova 1993):

$$\begin{aligned}
 \rho \frac{d\bar{v}}{dt} &= \bar{g}\rho & 1a \\
 &- \text{grad} p & 1b \\
 &+ \eta \nabla^2 \bar{v}^0 & 1c \\
 &+ \left(\frac{\rho^+ z^+ e_0}{m^+} + \frac{\rho^- z^- e_0}{m^-} \right) \bar{E} & 1d \\
 &- \frac{kT}{m^+} \text{grad} \rho^+ - \frac{kT}{m^-} \text{grad} \rho^- & 1e
 \end{aligned}
 \tag{Eq 1}$$

where:

ρ = density of the solution

ρ^{\pm} = density of the medium of the positive (negative) ions

\vec{v} = velocity of the solution (center of mass)

\vec{v}^0 = velocity of the solvent

\bar{g} = acceleration of gravity

p = pressure

η = shear viscosity coefficient

z^{\pm} = charge of an ion

e_0 = elementary electric charge

m^{\pm} = mass of a positive (negative) ion

\vec{E} = strength of the electric field of the system

k = Boltzman constant

T = temperature

The terms on the right side of the equation are associated with the following forces: 1a is the component of force due to gravity; 1b designates the force component due to pressure; 1c is the component due to viscosity; 1d is the force component due to EO; and 1e represents the component due to temperature.

The dominant force components are generally those due to pressure and electro-osmosis. In applications for preventing water seepage, where the seepage is caused by hydrostatic pressure, the electro-osmotic force must balance or exceed the hydraulic pressure force.

For EO to be effective, capillary pores must be present in the medium, the medium must have fixed surface charges (clays, concrete, and related materials are common media), the medium should be saturated, and the fluid must be a dilute electrolyte. The velocity equation of the pore solution is:

$$V_e = \frac{\varepsilon \xi E}{4\pi \nu l} \quad \text{Eq 2}$$

where:

V_e	=	flow velocity of solution (meters/second [m/sec])
ϵ	=	dielectric constant of water (Farads/meter)
ξ	=	zeta potential*
E	=	potential applied across material (Volts [V])
ν	=	viscosity of liquid (centipoises)
l	=	distance between electrodes (meters).

Equation 2 can also be expressed in terms of the current density:

$$V_e = \frac{\epsilon \xi j}{4\pi \nu \sigma} \quad \text{Eq 3}$$

where:

V_e	=	flow velocity of solution (m/sec)
ϵ	=	dielectric constant of water (Farads/m)
ξ	=	zeta potential (V)
ν	=	viscosity of liquid (centipoises)
j	=	current density (Amperes/m ²)
σ	=	electrical conductivity of material (Siemens/m)

The water and ions form an electrolyte where the positive ions tend to be solvated[†] and the negative ones unsolvated. So, as the positive ions move through the pores, the water molecules move as well. The water movement in practice is therefore heavily dependent on ion concentration, type of material, and magnitude of applied electric field. Of the independent variables, E can be controlled to redirect the movement of the solution.

Experimental Approach for Laboratory Studies

The laboratory work in this project was undertaken to qualify the range of hydraulic pressure heads that might be found in the field, and to quantify the effectiveness of EOP technology in concrete against these hydraulic pressure heads.

* The difference of potential between the plates of a hypothetical capacitor used to model the diffuse layers in the capillary structure.

† Formed by chemical or physical combination of a solute (ions) and solvent (water).

The laboratory studies are presented here in two parts:

- The process and procedure for the preparation of the laboratory specimens is documented to explain material characteristics and to enable repeatability of the experiments.
- The experimental procedure for the data collection is outlined and discussed to clarify the format of the laboratory setup and results.

To determine the effectiveness of EO to transport water against varying hydraulic pressure heads, a laboratory experiment was designed, equipped, and assembled to determine the range of performance of concrete under the influence of EO. Several experimental specimens of concrete block were prepared and tested. The hydraulic pressure head on the cathode side of the test cell was varied, while all other variables were held constant (Table 1). Four hydraulic pressure heads between 15 and 30 ft were chosen. Each concrete specimen was tested with a different hydraulic head to determine the effectiveness of EOP technology against different hydraulic pressures.

Table 1. Experimental design parameters that affect EO performance.

Parameter	Quality
External hydraulic force	Variable
Pore size/structure	Constant
Pore solution chemistry	Constant
Pore solution viscosity	Constant
Electrical potential	Constant
Waveform (time+/-)	Constant
Homogeneity of electrical field	Constant
Gravity	Constant
Temperature	Constant

The external hydraulic pressure served as the driving force that EOP had to work against. The hydraulic force was generated on the cathode face of the concrete test cell using a column of doped tap water (0.1 molar NaCl [saline] solution) under the influence of a pressure reducer. Adjusting this pressure reducer allowed for the variable hydraulic heads that EOP was tested against.

The pore size and structure provided the void matrix through which water could flow within the concrete test cell. The interconnection of these pores played an important role in the water transport rate, as did the pore radii. A more interconnected pore structure allowed for easier transfer of water through the cell. A

larger pore radii network allowed for preferential transfer of water through a less resistive passage.

It should be noted that, due to the nature of concrete and its placement, the pore size and structure were not completely constant throughout the experiment. Pore size and structure varied between test cells and within a single cell; however, since the same mix and placement of concrete were used for each cell, it is assumed to be relatively constant.

The pore solution chemistry is what allows EOP to draw water through a medium. The technology needs an ionic solution in order to draw a fluid through a pore matrix. Higher molar concentrations of ions in solution allows for greater effectiveness of EOP. In this experiment, the 0.1 molar NaCl solution simulated groundwater conditions.

Pore solution viscosity affects EOP's ability to draw water through any given pore space. Viscosity is a measure of a fluid's resistance to flowing, so that higher viscosities have lower flowability. A higher pore solution viscosity would reduce the effectiveness of EOP.

Electrical potential is the force that drives EO. Current created from a direct current (DC) voltage source is what allows EOP to drive ions through a medium.

The waveform generates a controlled, apparently alternating current (AC) from the DC voltage source. A controlled waveform was sourced from a computer program and held constant throughout the experiment. See the waveform discussion (page 14) for further details on waveform pattern. Also,

- The homogeneity of the electric field throughout the test cell from cathode to anode was assumed to be constant due to the equal resistance of the concrete throughout the specimen.
- The effect of gravity on the specimen was held constant (the specimen orientation was not varied.)
- The temperature in the laboratory was held as constant as possible.

Preparation of Cast Concrete Specimens

The cast concrete test specimens were composed of a uniform mix of Type I Portland cement, fly ash (Pozzolan), coarse aggregate (natural gravel), fine aggregate (natural concrete sand), and tap water. A computer program developed by the National Institute of Standards and Technology was used to calculate the exact

amounts of each type of material by weight that should be used to achieve the desired mix of concrete. (See the Appendix for exact batch mix specifications.) With the quantity of the material specified, the concrete was mixed using a small concrete mixer in accordance with American Society for Testing and Materials (ASTM) standard C192/C192M-98.

After the batch had been sufficiently mixed, nine standard test cylinders were poured in accordance with ASTM standard C31. After pouring, the specimens were cured in open air for at least 24 hours. Then they were placed in a tank of room-temperature water where they remained for the rest of their 28-day curing time.

Test Cell Preparation

To test the effect of EOP technology on concrete, the concrete cylinders had to fit into a test cell that could be installed into the experimental apparatus. To create a test cell, the concrete cylinders had to be cut into 4-in. tall specimens (Figure 1).

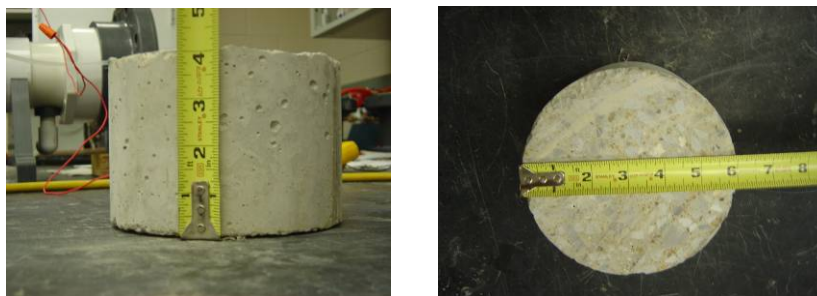


Figure 1. Profile and plan views of concrete cylinder specimen.

Once cut to size, the concrete cores were installed into a polyvinyl chloride (PVC) pipe with flanges on either end (Figure 2). The core was held in place by one coat of E6000 medium viscosity epoxy, layered under one coat of E6100 high viscosity epoxy. The epoxies effectively kept the core from shearing and prevented water from transferring along the PVC-concrete interface.



Figure 2. Profile and plan views of test cell.

With the concrete core in place, the test cell needed vertical holes drilled in the concrete face in order to later install probes. This was done with a normal drill bit of appropriate diameter. Four holes were drilled at the corners of a 4-in. square centered on the middle of the specimen. The holes in two opposing corners were drilled to depths of $L/3$ (1-1/3 in.) and $2L/3$ (2-2/3 in.).

After the holes had been drilled, the test cell was sealed on both faces using the E6100 high viscosity epoxy. The epoxy was applied in a thick coat along the inner face of the PVC pipe from concrete face to the outer edge of the PVC, and approximately 1 in. onto the concrete face itself. After the E6100 coat had time to set, a coat of E6000 medium viscosity epoxy was applied over the E6100 coat in order to fill in any gaps that may have formed during curing. No water could transfer along any gaps in the PVC-concrete interface or through the PVC itself. (**Note:** The holes must be drilled before the epoxy is placed because the vibratory action of the drill may damage the epoxy matrix, creating unwanted voids and cracks.)

After 3 days, the epoxy was sufficiently set to begin probe and anode installation. The probes used are stiff copper wire covered in an insulated heat shrink rubber. To create the probes, the copper wire was cut to length so that two extended ~ 3 in. beyond $L/3$ and two extended ~ 3 beyond $2L/3$. One end was sharpened to a point using a grinder and covered with heat shrink tubing from the sharp point up to 1 in. from the other end of the probe (Figure 3). To prepare the anode, it was bent at about the one-quarter point to approximately 12.5 degrees.

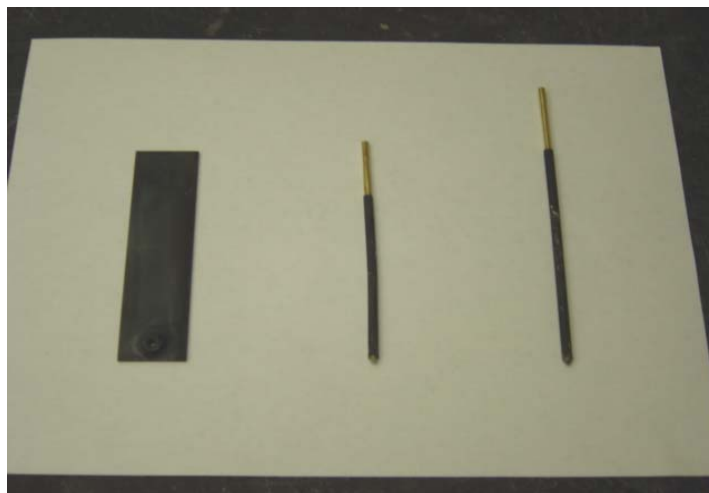


Figure 3. Unbent anode (left), probe to be installed to $L/3$ (center), and probe to be installed to $2L/3$ (right).

Once the anode and probes had been prepared they could be installed into the test cell. Grout mix consisted of a 75:25:50 ratio of Portland cement:sand:water. The probes were grouted securely into place so that the sharp point was in good contact with the concrete at the bottom of the predrilled hole (a slight tap with a hammer can improve contact.) The anode was grouted securely onto the concrete face so that there was a sufficient layer of grout between the concrete and anode and also a sufficient layer of grout covering the anode. After grouting was completed, 2 days were allowed for curing.

With everything grouted in place, a final coat of E6100 high viscosity epoxy was applied to both sides of the test cell (Figure 4). This final coat of epoxy was allowed 1 week to set up, and the test cell was ready for testing.

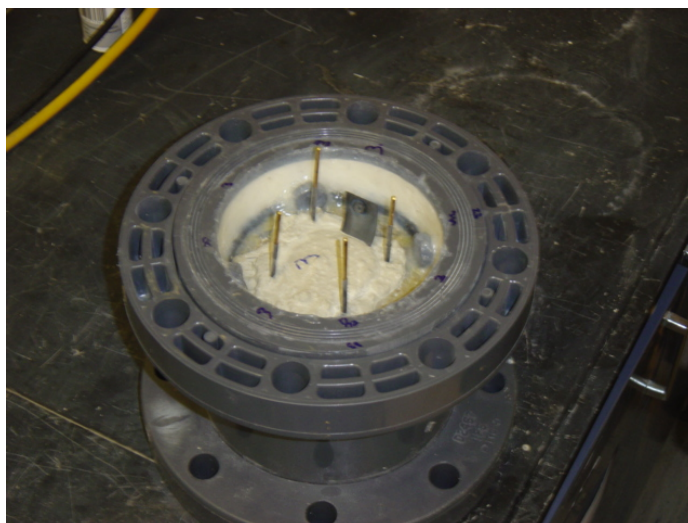


Figure 4. Test cell with probes and anode grouted in place and ready for testing.

Experimental Apparatus

The experimental apparatus was the setup used to test all of the test cells created. The setup itself (Figure 5) consists of PVC piping sealed at the top end and open at the bottom end. The top end has a threaded cap for water placement. The bottom end has a flange that matches up with the test cells. Within the setup itself, several key features enable the experimental process. The first feature is a pressure reducer (Figure 6) that allows air pressure from an outside source to be adjusted from 0 ft of hydraulic head to 35 ft of hydraulic head. At the base of the setup is a valve for releasing air and water. Within the setup, a cathode (Figure 7) is connected to a wire that connects externally to a voltage source.



Figure 5. Test setup.



Figure 6. Pressure reducer.

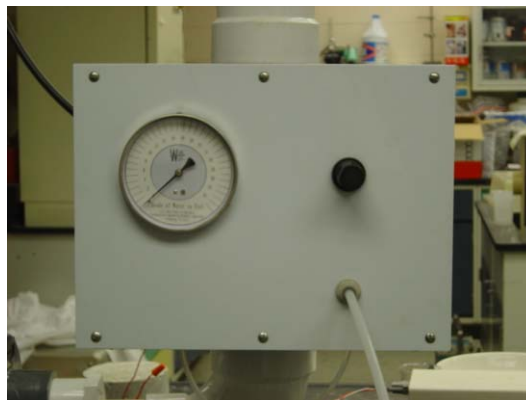


Figure 7. Cathode within experimental setup.

The external voltage source comes from a DC power supply (Figure 8) that is wired to the cathode and anode (after test cell installation). However, this DC power supply is changed into a simulated AC power supply using LabVIEW (National Instruments, Austin, TX), a waveform software application (Figure 9). Simulating AC power gives a more accurate depiction of real-life EOP applications. Figure 10 shows the EOP waveform pattern used.



Figure 8. DC power supply.



Figure 9. LabVIEW screen.

A waveform voltage that alternated between +30 VDC, 0 VDC, and -30 VDC was used because it was within the range used in the commercially available EOP system and because it was low enough to prevent overheating of the concrete and water (electrolyte) due to ohmic losses, $V = I^2R$.

The cathode side of the tank was filled with 6 liters of 0.1 molar NaCl solution. The anode side was empty and exposed to atmospheric pressure. In this way hydraulic gradients equivalent to a 30-ft water column (13.0 psi) and a 15-foot water column (6.5 psi) was applied across the sample.

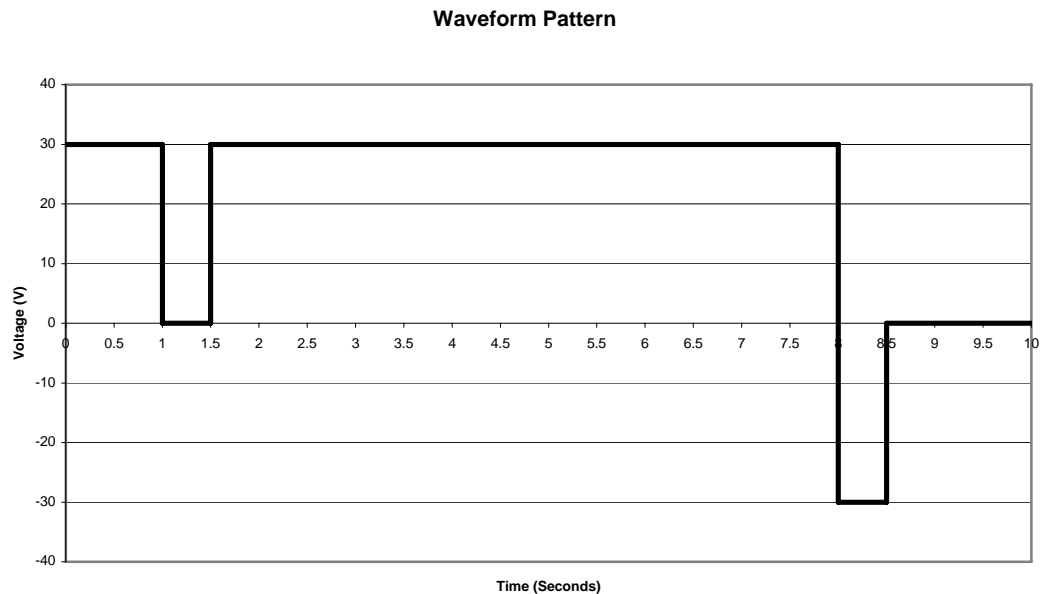


Figure 10. Waveform pattern used to generate a simulated alternating current.

Test Cell Installation

Once the epoxy in the test cells had time to set, the test cells could be installed onto the experimental apparatus (Figure 11). A rubber gasket coated with silicon was placed between the test cell flange and the experimental apparatus flange, which provided a watertight lock between flanges. The test cell was then held securely in place with eight bolts and hex nuts tightened to a degree that would not warp the PVC flange. Once secured, the silicon was given 2 hours to set.

At the concrete face, a wire was secured to the bent portion of the anode, creating a circuit between the cathode, anode, NaCl solution, and the voltage source. (**Note:** In three of the test runs, the test cell was installed on the experimental apparatus dry. Due to the high resistivity of concrete, and the resulting low currents, however, the final two samples were presoaked in 0.1 NaCl solution for three days. This procedure greatly lowered the effective resistivity of the concrete mass, increasing the current through the system. This more closely matched conditions expected in the field.)

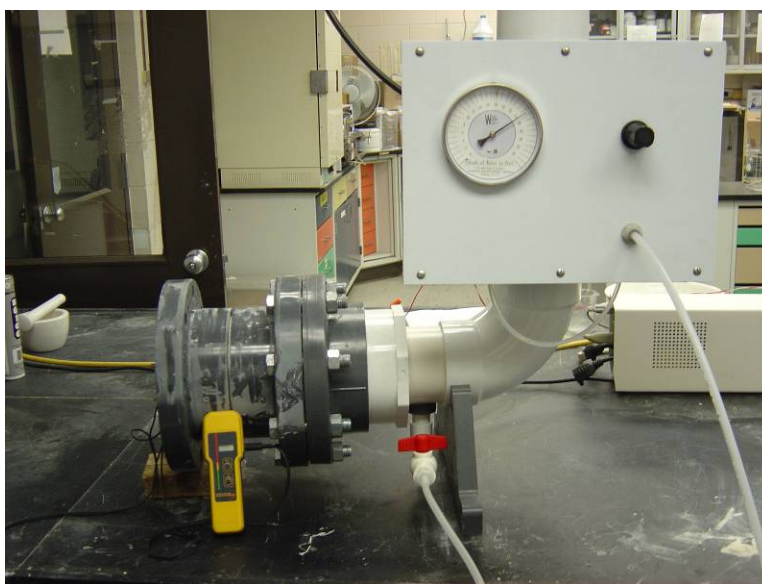


Figure 11. Experimental setup with test cell installed at left.

Experimental Procedure for EOP Data Collection

Once the silicon had cured, the testing could begin. First, the experimental apparatus was filled with 7.0 liters of a 0.1 molar NaCl solution (using the threaded cap near the top of the setup.) Next, the air pressure was applied to the system and the pressure adjusted to the desired setting using the pressure reducer. An initial reading was then taken at $L/3$ and $2L/3$ using the embedded probes and a GE Protimeter (General Electric North America, Billerica, MA) moisture meter (Figure 12).

For the non-pres soaked test cells, 1 week was given to allow the NaCl solution to infiltrate under pressure into the concrete test cell. Moisture meter readings and pressure readings were taken daily to track the advancement of water into the test cell. After 1 week, EOP was activated by turning on the DC voltage source and the waveform program. From this point on, maximum voltage readings and current readings were taken from the voltage source using a digital multimeter (Figure 13) in addition to the moisture meter and pressure readings. These readings were continued for 2 weeks or until equilibrium was reached. After the test, the water was drained and the core was removed, labeled, and monitored for any significant changes.

In the case of the presoaked test cells, no time was given for the NaCl solution to infiltrate the concrete test cell since the cell should have been saturated. Instead, EOP was immediately activated, and voltage, current, moisture meter, and pressure readings taken daily. Once the experiment reached equilibrium,

the water was drained, and the core was removed, labeled, and monitored for any significant changes.



Figure 12. Taking moisture reading from test cell.



Figure 13. Digital multimeter.

(**Note:** the effective surface area for water flux after the epoxy coatings had been applied could be approximated by a circle with a radius of 2 in. This would yield an effective surface area of 12.5 in.².)

3 Laboratory Results

In this experiment, two experimental procedures were used during test cell preparation. The first procedure involved a dry test cell. This test cell was allowed to dry for 1 month before being installed into the test apparatus. The second procedure involved the use of a saturated test cell. This test cell was immersed in a 0.1 molar NaCl solution for 3 days to achieve saturation. The results of these two different experimental procedures are discussed independently of each other.

The primary data collection method in the experiment was to record the moisture content within the concrete under varying levels of hydraulic pressure. In addition to moisture content within the concrete, data were collected on several other experimental parameters: electrical current, voltage drops across the sample, and hydraulic pressure. This data aided in analyzing the experimental setup and water content curves, and provided an insight into the behavior of EO in concrete.

Current and water transported via EO are directly related. Equation 3 indicates that velocity is directly proportional to current density and inversely proportional to the electrical conductivity. Current is charge moved per unit time (dq/dt) and EO is movement of water via positively charged ions. The relationship is direct, but not one-to-one. The energy supplied does not go totally to water transport; some goes to gas generation at the anode (oxidation) and cathode (reduction), and some goes to heat (I^2R).

Electrical current readings were recorded across the sample to monitor for increased resistance to current flow (decreased conductivity), which would result in a loss in efficiency.

Hydraulic and Electro-Osmotic Effect on Moisture Content in Dry Cells

Figure 14 shows the moisture content versus time for the dry test cell tested against 15-ft hydraulic pressure. The data from this experiment clearly show an initial rise in moisture content due to the application of hydraulic pressure. The data also clearly show a decrease in moisture content once EOP technology was applied, which indicates that EOP technology has the capability of drawing water against a 15-ft hydraulic pressure.

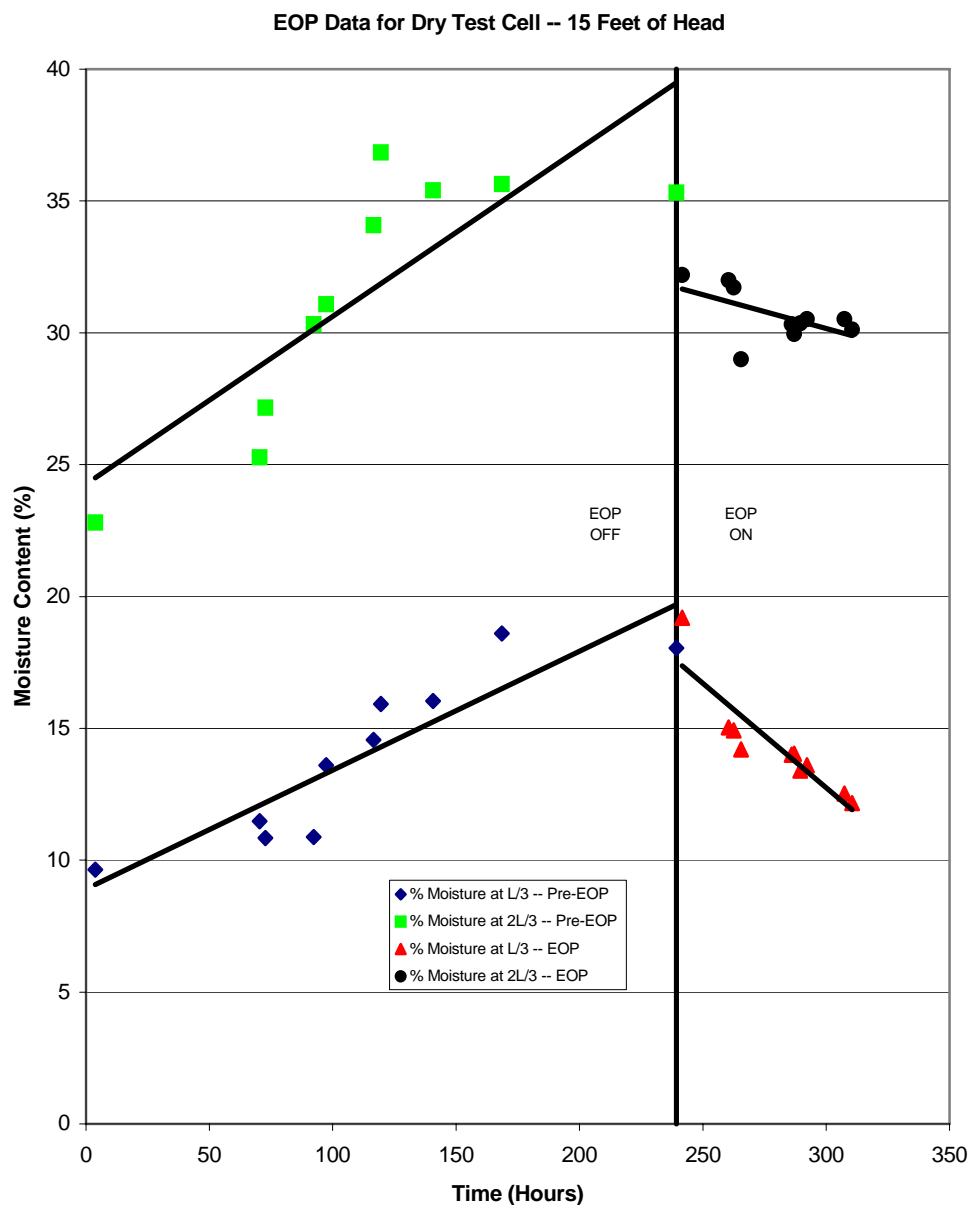


Figure 14. Moisture content vs time for dry test cell, 15-ft hydraulic pressure.

Figure 15 shows the moisture content versus time for the dry test cell tested against 20-ft hydraulic pressure. The data from this experiment clearly show an initial rise in moisture content due to the application of the hydraulic pressure. Over time, this increase in moisture content ceased as the test cell reached equilibrium. The data also clearly show a decrease in moisture content once EOP technology was applied, which indicates that EOP technology has the capability of drawing water against a 20-ft hydraulic pressure.

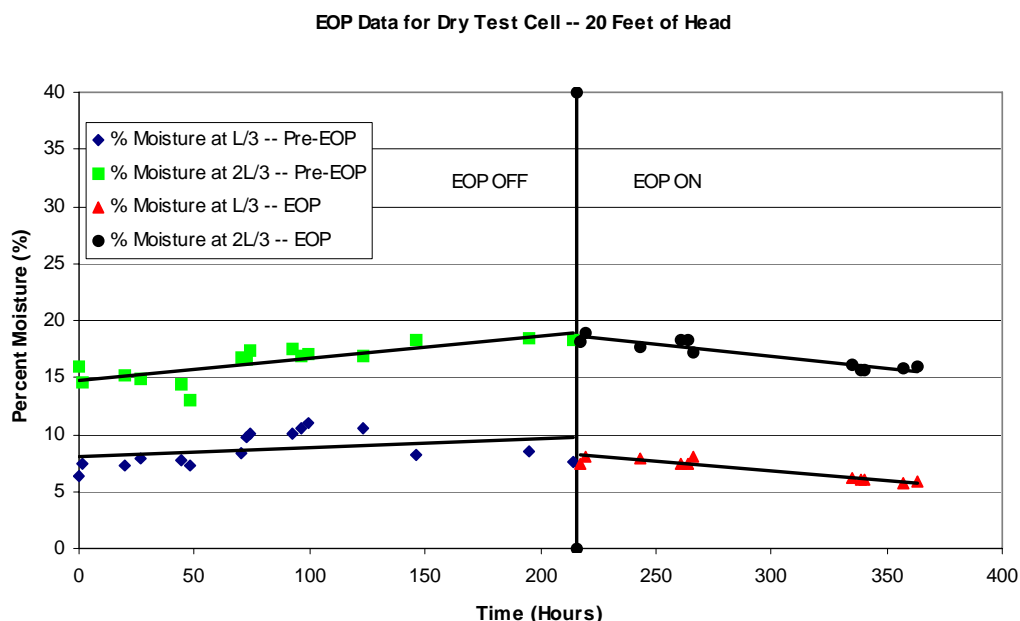


Figure 15. Moisture content vs time for dry test cell, 20-ft hydraulic pressure.

Figure 16 shows the moisture content versus time for the dry test cell tested against 30-ft hydraulic pressure. The data from this experiment show a dramatic rise in moisture content two-thirds into the axial length of the test core, and a moderate increase in moisture content one-third into the axial length of the test core. Over time, this increase in moisture content ceased as the test cell reached equilibrium. With the application of EOP, the test cell began to show some decrease in moisture content, but only a minor decrease persisted over time. This would indicate that EOP technology has some limitations working against 30-ft hydraulic pressure.

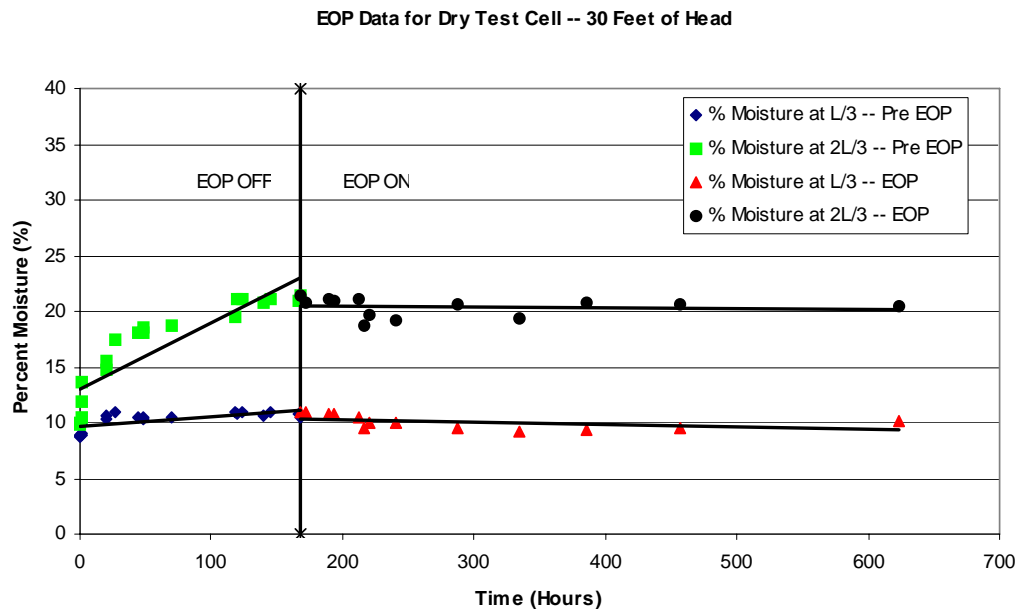


Figure 16. Moisture content vs time for dry test cell, 30-ft hydraulic pressure.

Hydraulic and Electro-Osmotic Effect on Moisture Content in Saturated Cells

Figure 17 shows the moisture content versus time for the saturated test cell tested against 25-ft hydraulic pressure. The data initially show a rapid decline in the test cell under the influence of EOP technology. However, the rate of moisture content decrease lessened dramatically with time. At one-third of the axial length of the test cell, the moisture content reached an equilibrium wherein the moisture content failed to decrease at all with time. At two-thirds the axial length of the test cell, the moisture content actually began to increase slightly before reaching equilibrium.

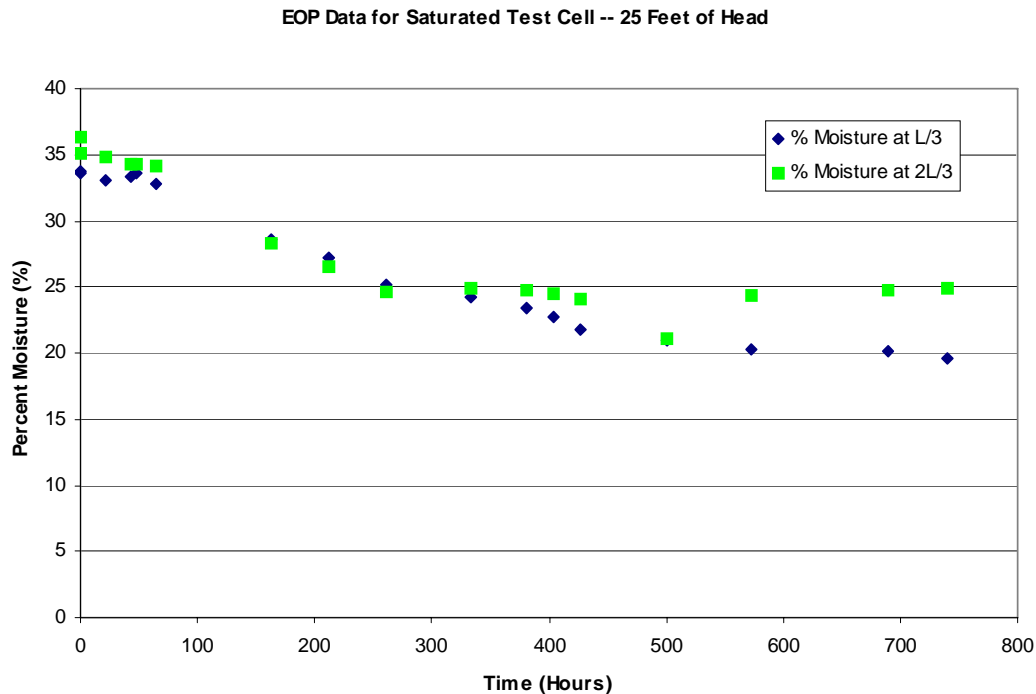


Figure 17. Moisture content vs time for saturated cell, 25-ft hydraulic pressure.

Some fraction of the decrease in moisture content in the saturated test cell occurred due to diffusion. To measure this, a saturated test cell was installed into the test apparatus without turning on EOP. Figure 18 shows the results of this experiment. These results show that diffusion does occur in the test cells, and that some moisture is lost from a test cell without the presence of EOP.

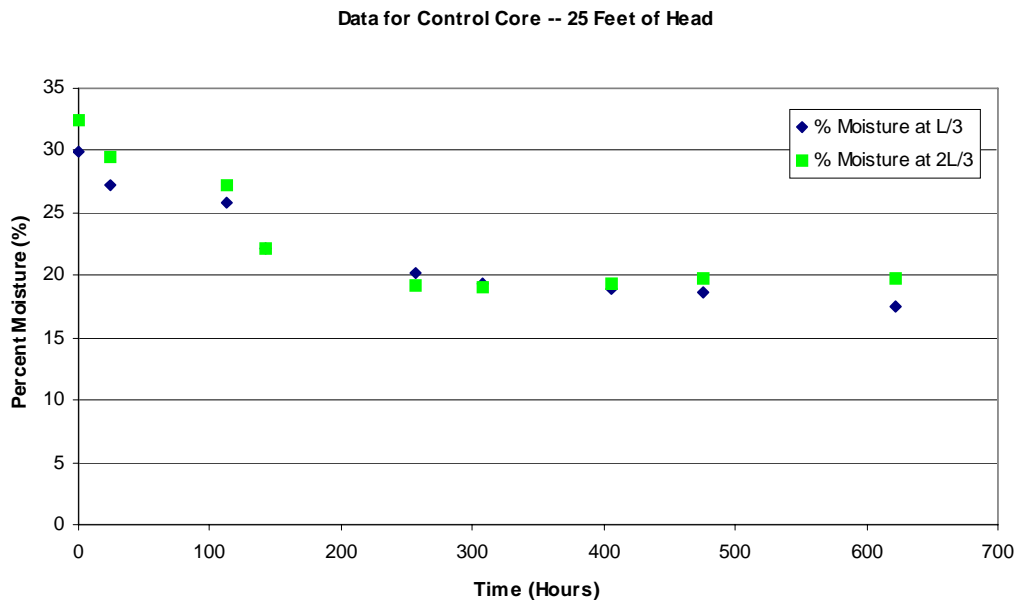


Figure 18. Moisture content vs time for saturated test cell not under influence of EOP.

Electrical Current Through the Test Cells

A noticeable difference in measured current was found to exist between the dry test cells and the saturated test cell. In the dry test cells, the current flow was almost negligible (less than 0.1 mA) throughout the life of the experiment. This low flow was due to the high resistivity of the concrete test cell in a dry state. For the cell saturated in the 0.1 molar NaCl solution, however, the resistivity of the concrete was greatly reduced by the presence of ions from the saturation phase. Consequently, a much larger current was found to pass through the saturated test cell at the beginning of the experiment. Over time, though, the current through the test cell dropped as the ions were drawn out of the concrete during the EOP process. Figure 19 shows this phenomenon. The data clearly show a large current flow at the beginning of the experiment and almost no current flow at the end of the experiment. This drop in current flow could explain why EOP was more efficient at the early phase of the saturated test cell experiment than at the end. It could also explain why the moisture content went up at two-thirds the axial length of the specimen at the very end of the experiment (see Figure 17).

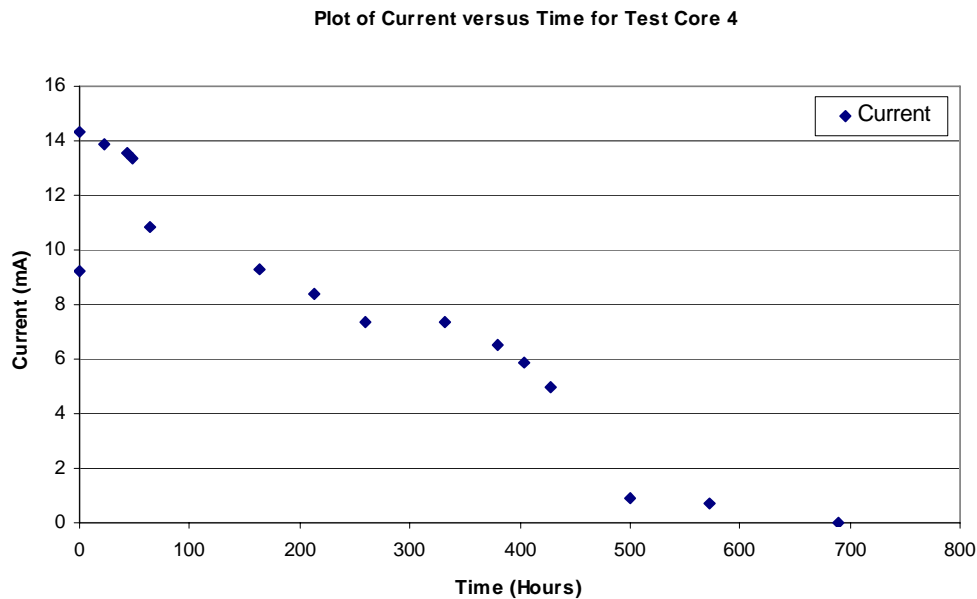


Figure 19. Current vs time for saturated test cell with EOP, 25-ft hydraulic pressure.

4 Field Demonstrations

EOP systems were installed in two lock structures on the Mississippi River in areas with chronic water intrusion: in the basement of the old lock house at Lock and Dam 7 at Dresbach, MN, and in a section of gallery tunnel between the main and auxiliary locks of Lock 27 at Granite City, IL.

Specialized Electrode Development

EOP installations typically involve relatively thin (up to 12-in.) concrete walls or floor slabs with soil on the exterior side. However, Civil Works structures are generally constructed of thick concrete cross-sections with rock, water, or soil on the exterior side. In addition, construction drawings of some lock and dam structures indicate water barriers exist embedded in the concrete walls. These water barriers reduce the effectiveness of the EOP system through disruption of the electric field set up within the concrete pores. To overcome these rather unique construction details, new and modified electrode designs were developed and constructed.

Anode Design

A typical anode wire as shown in Figure 20 is a titanium wire with a mixed metal oxide coating. (The mixed metal oxide greatly extends the life of the anode.) Figure 21 shows a probe anode that was developed for Civil Works structures. It is a 3/4-in. titanium steel tube, 4-in. long, with the mixed metal oxide coating.



Figure 20. Standard anode with lead wire.



Figure 21. Probe anode with lead wire.

Cathode Designs

Typically, the cathodes used with EOP systems are standard copper clad steel grounding rods (Figure 22). For Civil Works structures, special cathodes were designed and fabricated: probe cathodes (Figure 23) and copper plates (Figure 24). Short sections of grounding rods cut to 5-in. lengths were also used in one demonstration to evaluate any difference in performance between them and the specially fabricated probe cathodes.

EOP Installation at Lock and Dam 7

The old lock house at Dresbach Lock and Dam was constructed in 1935 when the lock and dam were constructed on the Mississippi River south of Dresbach, MN, near La Crosse, WI. The lock provides an 8-ft lift during normal conditions between the upper and lower pools.



Figure 22. Copper clad grounding rods.



Figure 23. Probe cathode.



Figure 24. Copper plate cathode.

EOP Design

The original plan for the EOP demonstration was to place cathodes on the bottom of the lock. Ted Engelein, the Lockmaster at that time, explained that it would be impractical to try to place something in the bottom of the lock such as a copper plate attached to a concrete block or a concrete filled copper pipe. Nothing placed in the lock like that would survive long. Prop wash is a problem that could be overcome with good anchoring, but the main problem is ice build-up in the winter. The water in the lock often freezes all the way to the bottom of the lock. In such cases, even though the water thaws in the spring, it thaws from the top down. Barges often bump into and move submerged ice around in the lock in the spring and anything on the bottom of the lock would be quickly torn out.

The only option available was to mount the cathode in the lock wall itself so that it is flush with the wall surface. This means the cathode has to be installed in either an existing wall cavity or one created especially for the cathode. The only viable options were to attach a plate cathode in the ladder recess in the lock or to drill a hole in the lock wall and place a probe type cathode in the hole.

The basement of the old lock house is an electrical vault through which all of the electrical controls for the dam pass. Water enters through the walls, floor, or electrical conduits. During high water, the room fills up with water, beyond the point where a small sump pump in the floor drain can keep up, to a point where a large auxiliary pump with switches about a foot off the floor, keeps the water level below that point. At times during spring flooding, they also need to sand-bag the old lock house to prevent the rising water from flooding inside. Last spring a portable pump was set up on the far lock wall to help pump water out of the crossover, which was pretty successful in keeping much of the water out of the electrical vault.

The final EOP design for the old lock house consisted of a standard EOP installation for the sides of the lock house not a part of the lock wall. This consisted of a wire anode at the floor-wall juncture and standard 8-ft long copper-clad grounding rods as cathodes, placed through the wall and into the soil around the lock house. The lock wall would be protected from water intrusion by installing a 12-in. copper plate in the lock ladder wall at the north end of the lock house and a probe cathode in the lock wall toward the south end of the building. In addition, to test and evaluate the performance of the probe anodes and probe cathodes, probe anodes were placed 2 ft apart along the lock wall, in addition to a normally installed wire anode. Probe cathodes were placed approximately 4 ft into the

lock wall at three locations: a pair at the north end of the basement, a pair at the middle, and a pair at the south end of the basement. Each pair of cathodes consisted of one probe cathode and one half-inch-diameter copper clad steel rod, 5-in. long, placed 6 in. apart. The purpose of the cathode pairs was to determine if any performance difference was detected between the two cathodes. Figure 25 shows the EOP installation layout.

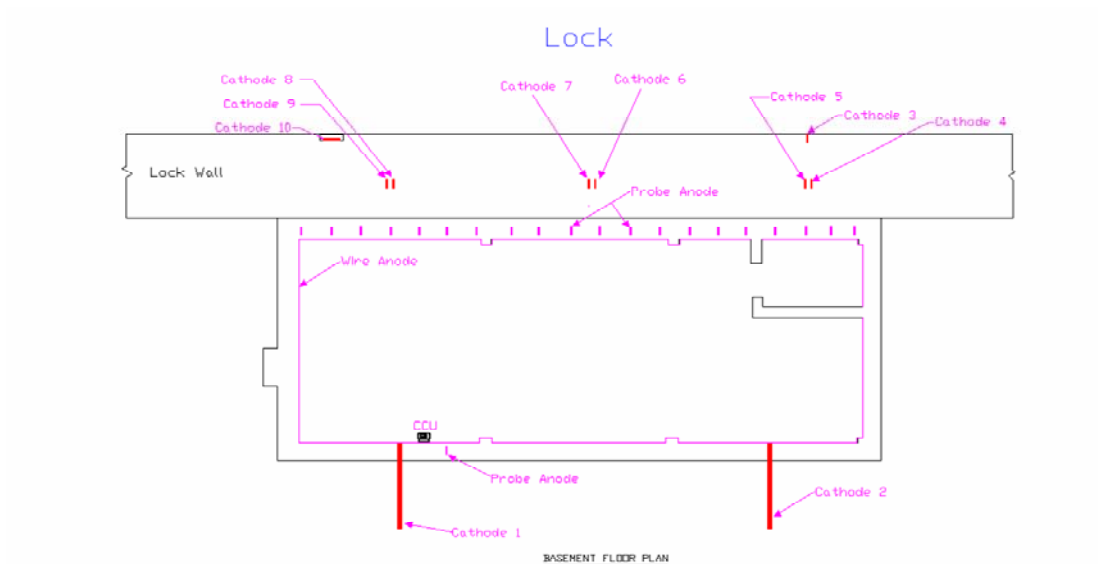


Figure 25. EOP Installation layout in basement of old lock house, Lock and Dam 7.

The EOP system was installed with the lead wires running in standard electrical conduit and connections for the various anodes and cathodes in standard electrical junction boxes. Figure 26 shows the location of the junction boxes around the basement, and Table 2 is a description of the EOP system wiring in each junction box.

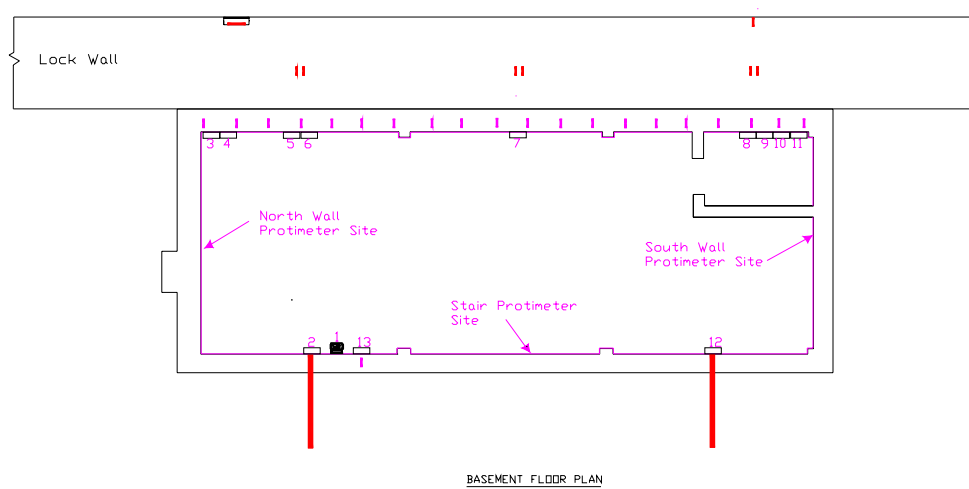


Figure 26. EOP junction box locations in basement of old lock house.

Table 2. Junction box wiring configuration at Dresbach Lock and Dam.

Box	Description
Moving clockwise around room from CCU	
1 (CCU)	Header Wires (anode and cathode) from Power Supply Anode Feed 1 Anode Feed 2 Cathode Feed 1 Cathode Feed 2 A1 A8 A9 C1
2	Cathode 1 (Copper rod into soil)
3 (W/S wall)	Anode Feed 1 Cathode Feed 1 A2 A3 C6 C7 C8 C9 C10
4	Cathode 10 (Plate)
5	Cathode 9 (Copper rod)
6	Cathode 8 (Probe)
7	Cathode 7 (Copper rod) Cathode 6 (Probe)
8	Cathode 5 (Copper rod)
9	Cathode 4 (Probe)

Box	Description
10	Cathode 3 (Probe)
11 (W/N wall)	Anode Feed 3 Cathode Feed 3 A4 A5 A? (yellow wire) C3 C4 C5 C6
12 (E/N wall)	Anode Feed 2 Anode Feed 3 Cathode Feed 2 Cathode Feed 3 A6 A7 C2 Cathode 2 (Copper rod into soil)
13 (E/S wall)	Probe anode

EOP Evaluation

After the EOP system was installed and activated, current and voltage were measured periodically to evaluate the performance of the EOP system, especially in the wall that faced the lock. Table 3 lists the data taken. In all measurements, the wire anodes along the wall-floor juncture were connected as were the two cathode rods in the soil-side wall. Each cathode on the lock wall was tied into the system separately or in combinations and the current draws and voltages measured. Then the two cathodes in the lock face were activated and current and voltage values measured with just the probe anodes activated and both the probe and wire anodes activated. Figure 27 is a graph showing the current draw over time for the two standard cathodes in the soil and each of the cathodes installed in the lock wall. Figure 28 shows the current draw over time for the wall cathodes and all of the probe type cathodes and short rod cathodes. Figure 29 shows the current draw over time for the wire anode, the probe anodes, and the two combined in conjunction with the plate and probe cathodes in the lock along with the two standard wall cathodes.

In addition to the current and voltage measurements, concrete moisture measurements were taken using a moisture meter. Table 4 shows the moisture measurements obtained. See also Figure 30 and 31.

Table 3. Voltage and current measurements over time at Dresbach Lock and Dam.

Active Components	At Lock Wall Activation		33 Days after Lock Wall Activation		91 Days after Lock Wall Activation	
	VDC	Amps	VDC	Amps	VDC	Amps
Base: Wire Anodes and West wall cathodes	31.72	0.6	33.9	0.635	34.5	0.495
Lock Wall Cathodes						
10 – Plate Cathode	34.51	1.17	32.1	1.103	34.2	0.585
3 – Probe Cathode	35.47	0.703	33.5	1.108	34.1	0.571
10 + 3 Cathodes	36.36	1.25	32.0	1.083	33.7	0.66
Basement Wall Cathodes						
9 – Copper Rod Cathode	35.09	0.725	33.3	0.74	33.9	0.613
8 – Probe Cathode	35.69	0.705	33.4	0.71		
7 – Copper Rod Cathode	34.56	0.727	33.4	0.733	33.8	0.6
6 – Probe Cathode	34.97	0.711	33.5	0.683		
5 – Copper Rod Cathode	35.36	0.725	33.4	0.693	33.9	0.602
4 – Probe Cathode	34.56	0.701	33.4	0.693		
9 + 7 + 5 Cathodes	34.67	0.92	32.7	0.949		
8 + 6 + 4 Cathodes	35.61	0.863	33	0.864		
Cathodes 10 and 3 activated						
Probe Anodes	36.92	1.27	32.1	1.173		
Probe + Wire Anodes	35.05	1.27	31.5	1.244		

Table 4. Wall concrete moisture measurements versus time.

Protimeter Readings	At Lock Wall Activation	33 Days After Activation	91 Days After Activation
Center of North Wall	10.6%	9.7%	12.1%
1	14.0%	13.6%	15.1%
Base of Stair	11.0%	12.8%	13.4%
2	17.0%	11.5%	14.5%
Center of South Wall	13.5%	13.2%	14.5%
5	18.5%	10.9%	12.6%
7	13.7%	11.9%	12.1%
9	12.9%	10.3%	12.3%

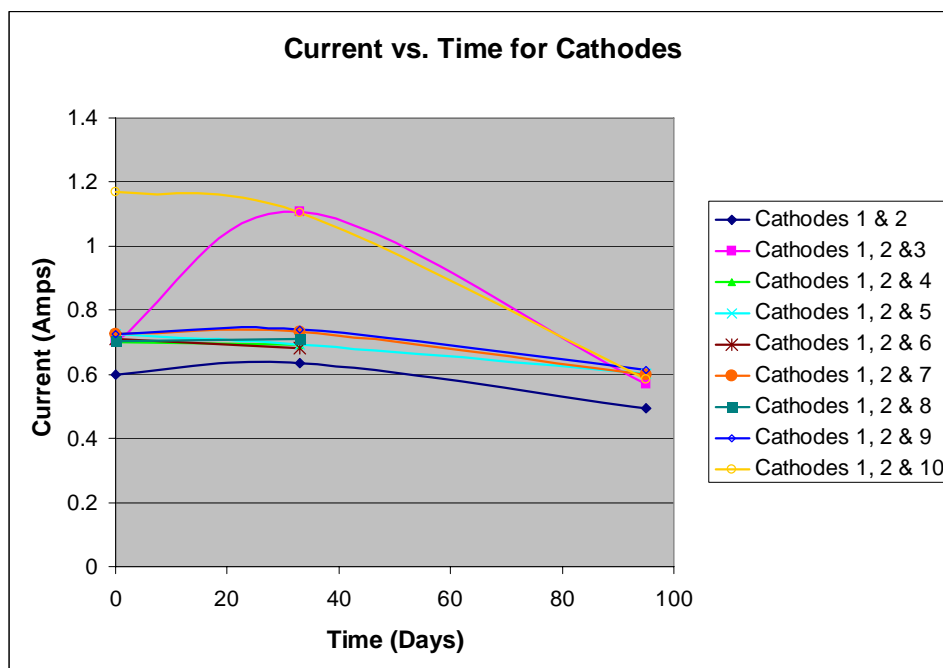


Figure 27. Current demand for cathode combinations vs time.

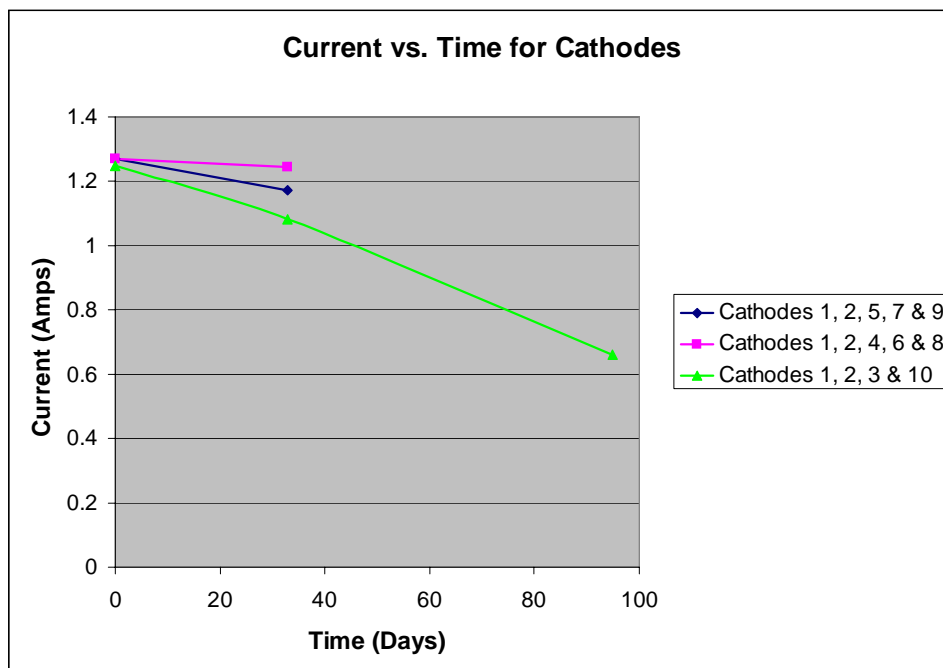


Figure 28. Current demand for multiple cathode combinations vs time.

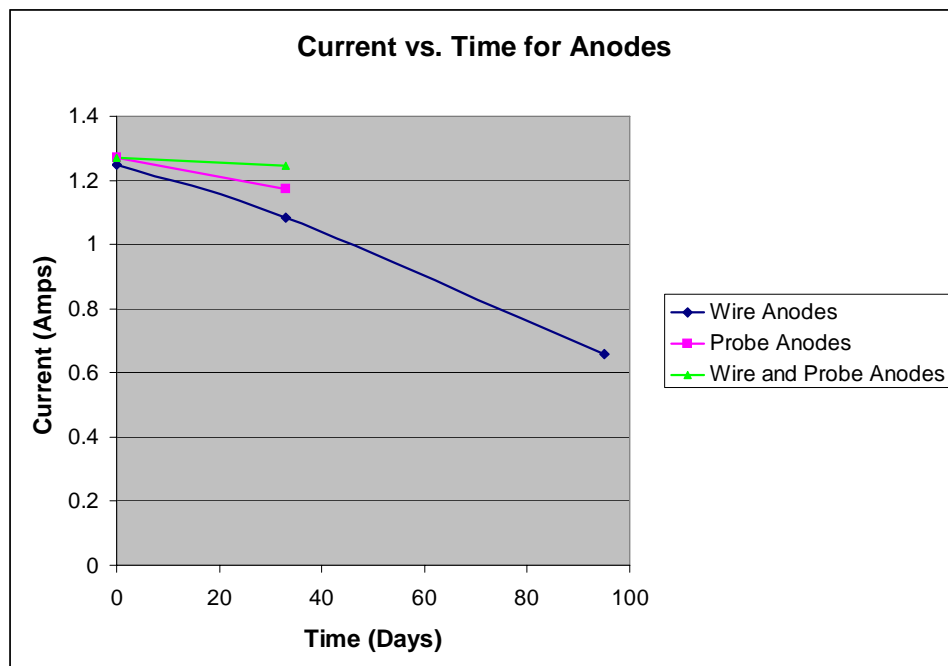


Figure 29. Current demand for anodes vs time.

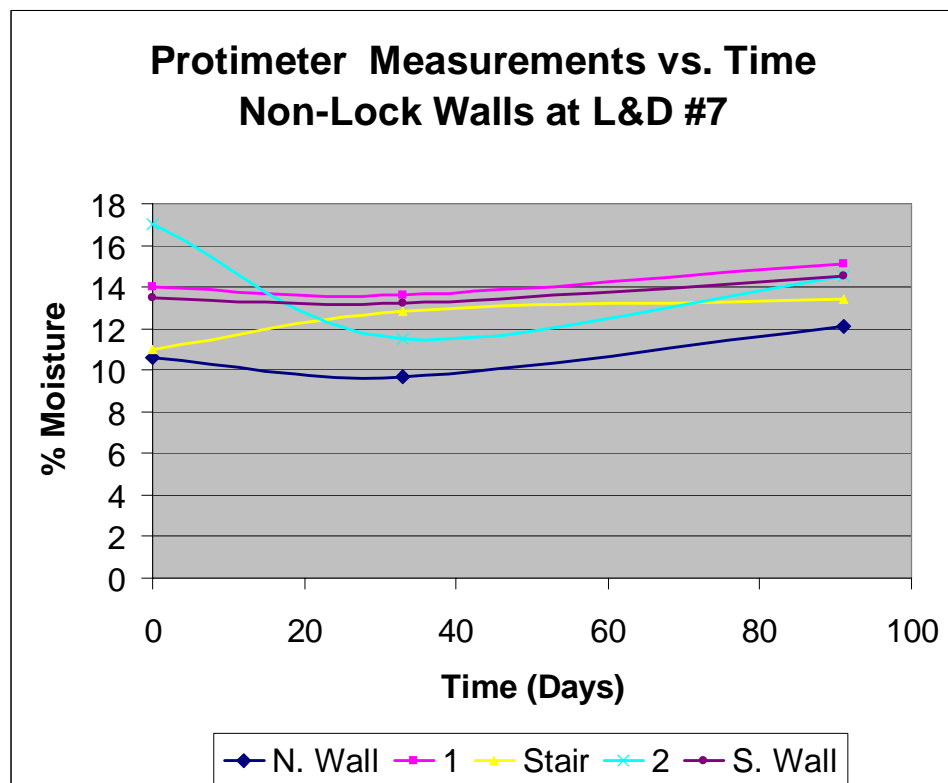


Figure 30. Protimeter measurements vs time for nonlock basement walls locations.

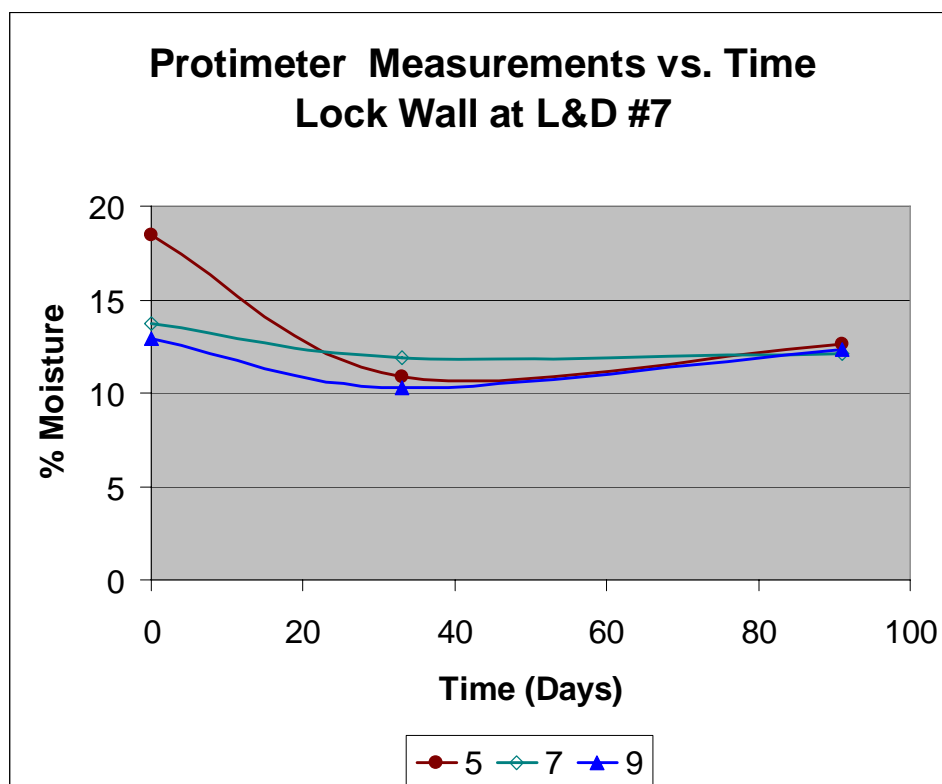


Figure 31. Protimeter measurements vs time for basement lock wall locations.

Visual Inspection of the EOP System Performance

An inspection of the installed system was conducted 7 July 2004 to take moisture, voltage, and current measurements. The sump pump in the central drain had quit working and the basement had 4 in. of standing water in it. Lock personnel were contacted and a new sump pump installed in the sump pit. According to lock personnel, water always comes up through the floor. Inspection of the basement walls revealed that the concrete was wet under the wiring conduit in the north side of the wall, and the paint had peeled at that location more than in surrounding areas.

By the following morning, the standing water in the basement had been pumped out with only a few inches of water in the sump pit and drain trench. The floor was wet. Investigation of the outside of the building indicated that the landscaping caused water to drain toward the building for perhaps 150 ft. Further inspection of the grounds around the old lock house revealed two locations where what appeared to be water drainage holes went under the lock house addition on the West side of the building opposite the lock. At one location, the downspouts for the roof drains ended just above one of the holes going under the building. A hose was attached to a hose bib at that location and water was allowed to run onto the ground between the downspouts. Within a few minutes, water began to

pour into the basement from the wiring conduit where the wall had been noted previously as being wet. The Dresbach area had had some severe rainstorms a few days previously and it is likely that the water from the roof and the surrounding area had entered the basement through the holes under the building addition.

The basement was found to be completely dry during a visit to the demonstration site 2 months later. It was noted that extensions had been added to the downspouts to divert water away from the building.

EOP Installation at Lock 27

The Lock 27 facility houses the lowest locks on the Mississippi River. The locks are in the Chain of Rocks Canal near Granite City, IL, a suburb of St. Louis, MO. Originally constructed in 1947, the locks have a typical lift of 12 ft between the lower and upper pools.

Water continually seeps through the walls in a section of the gallery in the structure between the main lock and the auxiliary lock below the lock control house. Although water comes through the galleries at other locations, this is one of the most chronic water-intrusion locations. This 52-ft long section was selected to demonstrate the EOP system.

The design for this location included standard wire anode installation on the inside of the gallery: at the floor-wall interface and also at the ceiling-wall interface. In addition, anode wire was installed in the walls, floor, and ceiling at construction joints that crossed the gallery. Six cathodes were installed: two copper plate cathodes, one in the floating mooring bit well on the main lock wall and one in the auxiliary lock ladder recess; and four probe cathodes, one in each wall at the north end of the section and one in each wall near the midpoints. The copper plates were 12-in. wide and 24-in. high. Figure 32 is a drawing of the plates used. Figure 33 shows the gallery section floor plan and cathode locations.

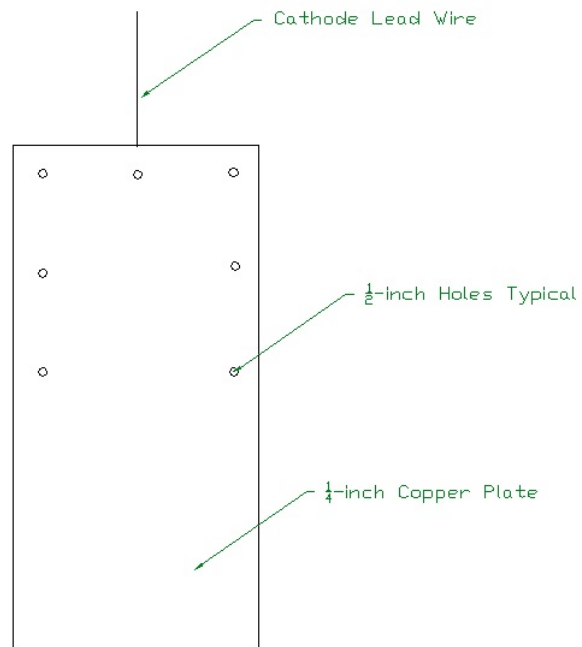


Figure 32. Plate cathode drawing.

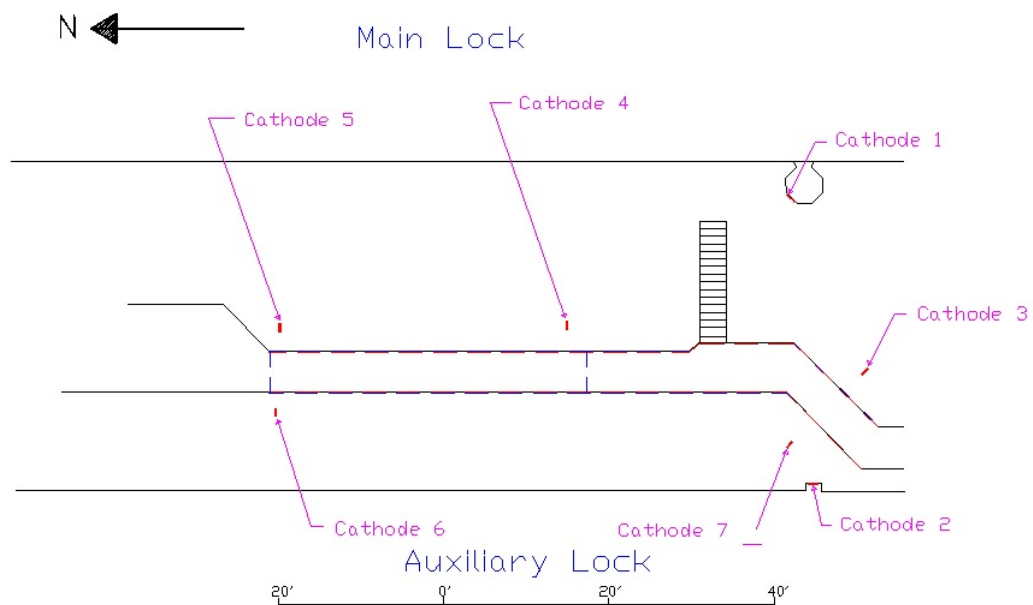


Figure 33. Gallery demonstration section floor plan.

Table 5 describes the EOP system wiring in each of the junction boxes.

Table 5. Junction box wiring configuration.

Box	Description
Control Room	
1	Header Wires from Power Supply Header Wires to Box 2
2	Header Wires from Box 1 Header Wires to Box 3 Cathode 1 connection Cathode 2 connection
3	Header Wires from Box 2 Header Wires to Box 4
Gallery	
Begin: east side, south end	
4	Header Wires from Box 3 Header Wires to Box 5 Header Wires to Box 24 One Anode Feed
5	Header Wires from Box 4 Cathode 3 connection Two Anode Feeds
6	Cathode 3
7	One anode dead end (no header wire)
8	Header Wire (anode) from Box 9 One Anode Feed
9	Header Wire (anode) from Box 10 Header Wire (anode) to Box 8 Two Anode Feeds
10	Header Wires from Box 13 Header Wire (anode) to Box 9 Cathode 4 connection Two Anode Feeds
11	Cathode 4
12	Header Wires from Box 20 Header Wires to Box 13 Two Anode Feeds
13	Header Wires from Box 12 Header Wires to Box 10 Header Wires to Box 16 Two Anode Feeds
14	Header Wire (anode) from Box 16 One Anode Feed
15	Cathode 5

Box	Description
16	Header Wires from Box 13 Header Wire (anode) to Box 14 Cathode 5 connection One Anode Feed
End: east side, north end	
Begin: west side, north end	
17	Header Wire (anode) from Box 18 Three Anode Feeds, all upwards (Expansion Joint)
18	Header Wires from Box 21 Header Wire (anode) to Box 17 Cathode 6 connection One Anode Feed
19	Cathode 6
20	Header Wires from Box 20 Header Wires to Box 12 Two Anode Feeds
21	Header Wires from Box 23 Header Wires to Box 18 Header Wires to Box 20 Two Anode Feeds
22	Header Wire (anode) from Box 23 Four Anode Feeds, all upwards (Expansion Joint)
23	Header Wires from Box 26 Header Wires to Box 21 Header Wire (anode) to Box 22 Two Anode Feeds
24	Header Wires from Box 4 Header Wires to Box 27 Two Anode Feeds
25	Cathode 7
26	Header Wires from Box 23 Header Wires to Box 28 Cathode 7 connection Two Anode Feeds
27	Header Wires from Box 24 Header Wires to Box 28 One Anode Feed
28	Header Wires from Box 27 Header Wires to Box 26 One Anode Feed
End: west side, south end	

Concrete moisture was measured at selected locations along the gallery using a moisture meter. Figure 34 shows where the moisture measurements were taken and Table 6 lists the percent moisture in the concrete at each location versus time. Figure 35 and 36 are graphs of the voltage draw for the system over time and the current draw over time respectively. Figure 37–42 are graphs of the moisture meter data taken. Location 22 is in the middle of the gallery ceiling and is included in Figure 40.

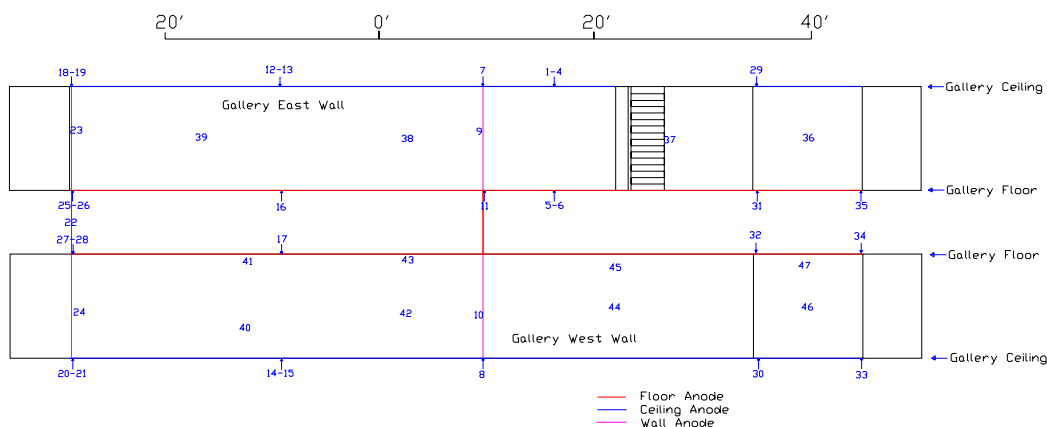


Figure 34. Protimeter measurement sites.

Table 6. Concrete moisture vs time in gallery at Lock 27.

Protimeter Reading Location	At System Activation	27 Days after Activation	66 Days after Activation
1	16.5%	18.0%	15.90%
2	14.2%	16.4%	16.30%
3	17.8%	19.7%	16.20%
4	16.0%	15.9%	14.70%
5	34.5%	20.6%	17.80%
6	22.2%	19.4%	17.60%
7	18.8%	19.4%	18.30%
8	15.9%	15.8%	15.40%
9	13.6%	15.7%	15.60%
10	15.6%	15.8%	15.40%
11	52.8%	22.1%	18.30%
12	17.3%	17.0%	14.40%
13	15.9%	15.7%	14.90%
14	18.1%	18.6%	17.80%
15	14.5%	12.5%	15.70%
16	17.7%	18.9%	16.70%
17	28.0%	21.0%	18.70%
18	17.1%	18.8%	17.40%
19	16.0%	17.1%	16.40%

Protimeter Reading Location	At System Activation	27 Days after Activation	66 Days after Avation
20	18.5%	18.4%	16.80%
21	15.9%	16.7%	15.90%
22	16.7%	16.1%	16.90%
23	15.2%	18.3%	16.30%
24	15.8%	17.9%	15.90%
25	22.7%	18.8%	20.30%
26	44.5%	21.7%	16.50%
27	48.1%	29.3%	20.30%
28	36.7%	25.9%	21.50%
29	19.7%	18.6%	17.80%
30	18.3%	18.7%	17.50%
31	31.5%	21.5%	17.90%
32	37.1%	21.4%	15.90%
33	19.1%	17.8%	16.80%
34	30.0%	21.6%	18.10%
35	46.1%	21.4%	16.90%
36	14.3%	14.2%	11.30%
37	12.1%	17.6%	12.90%
38	15.1%	19.3%	12.50%
39	14.2%	18.2%	12.70%
40	12.1%	-*	12.20%
41	18.5%	-	16.70%
42	13.2%	-	11.20%
43	18.8%	-	14.80%
44	15.1%	-	13.60%
45	17.4%	-	15.20%
46	14.0%	14.0%	15.80%
47	20.3%	-	17.90%

* Data not taken at (-) locations.

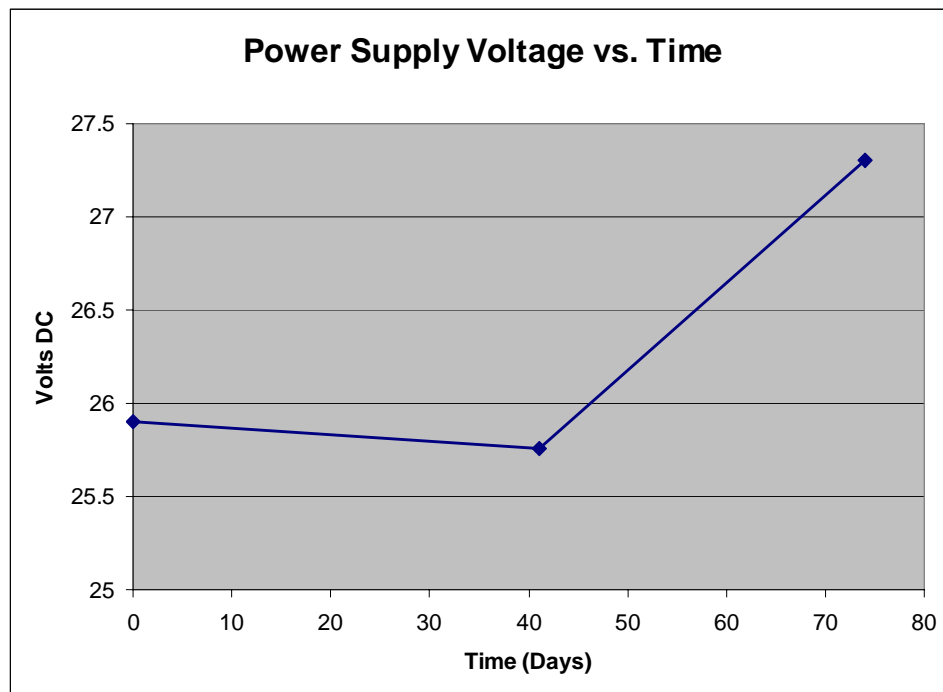


Figure 35. Voltage demand for EOP system vs time.

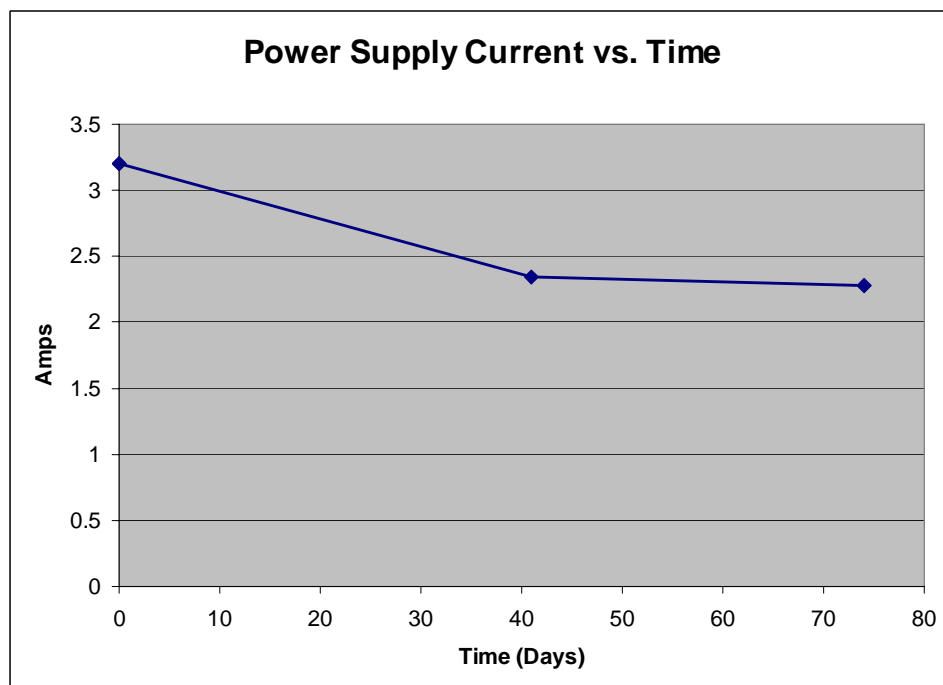


Figure 36. Current demand for EOP system vs time.

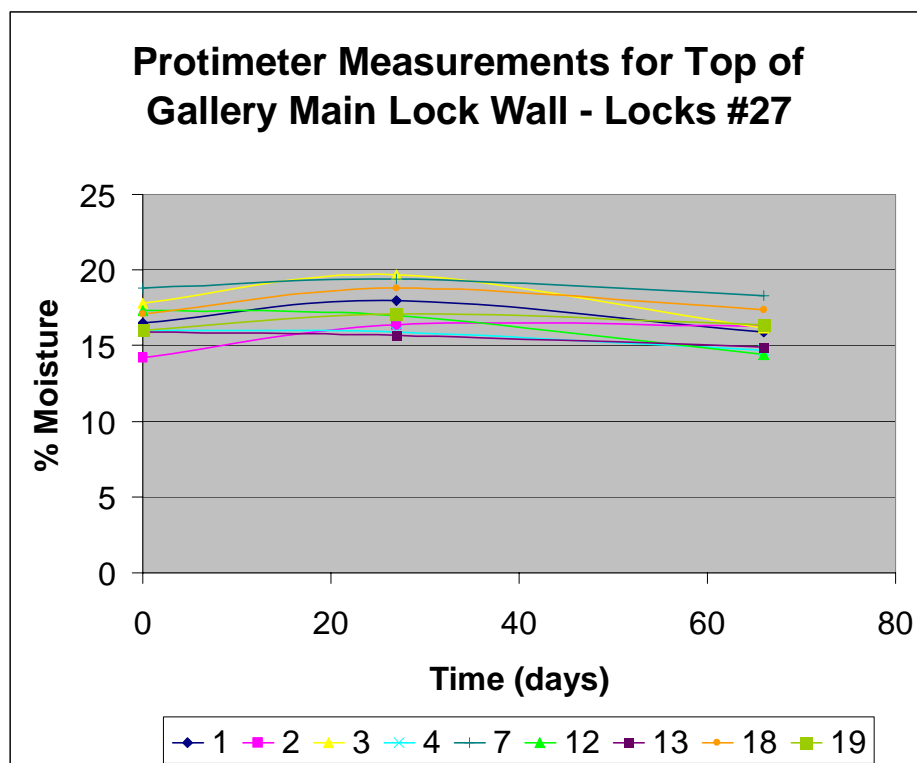


Figure 37. Graph of protimeter values at wall-ceiling juncture of gallery east wall.

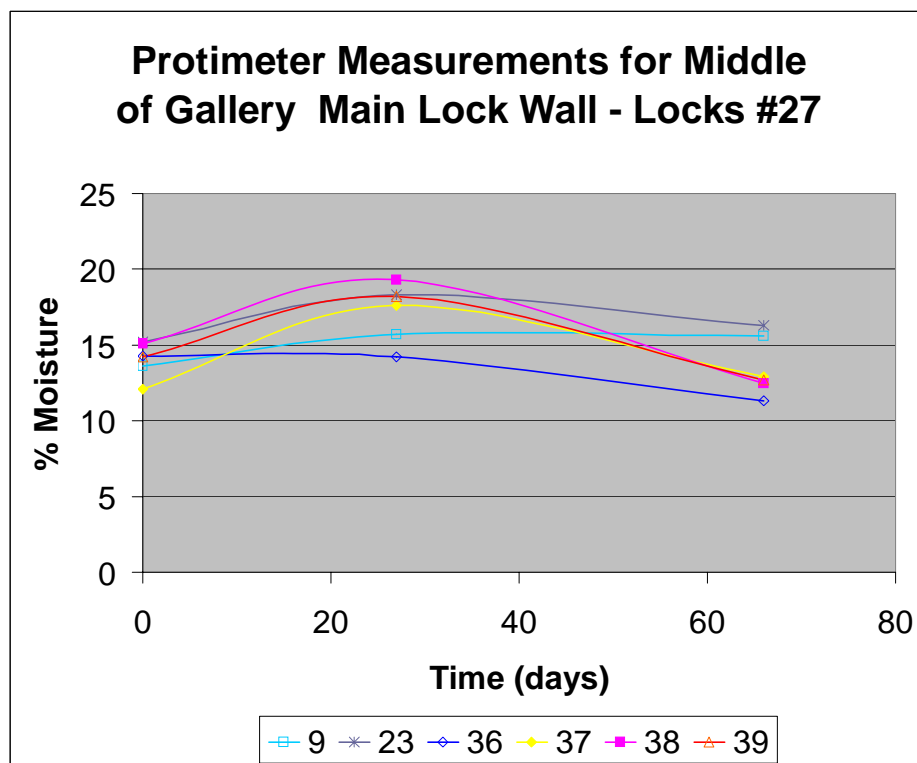


Figure 38. Graph of protimeter values on gallery east wall.

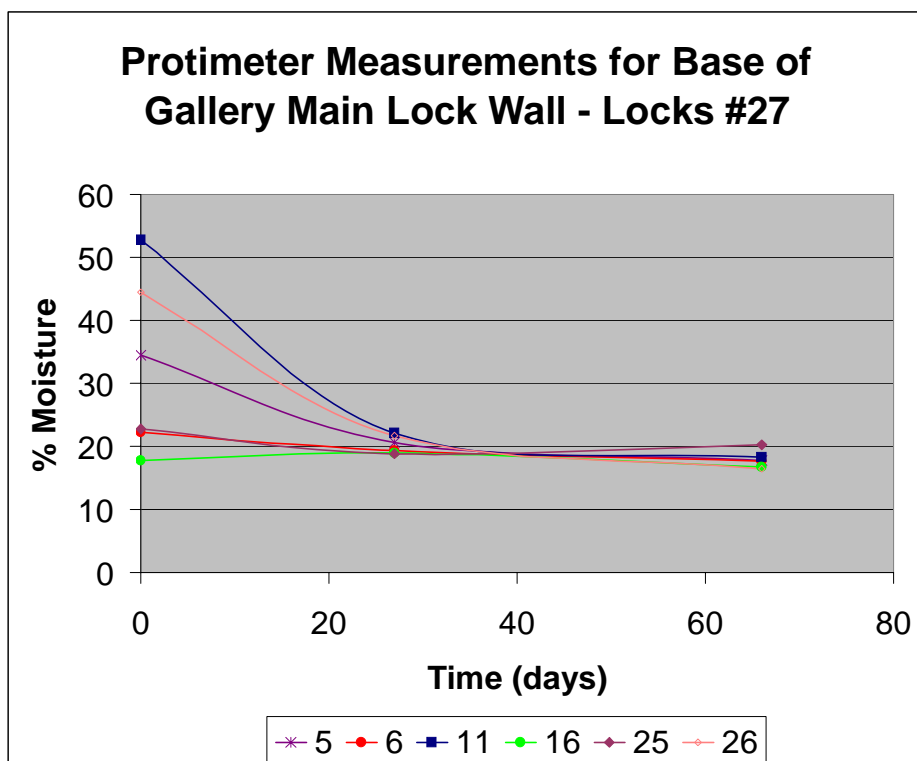


Figure 39. Graph of protimeter values at floor/ceiling juncture of gallery east wall.

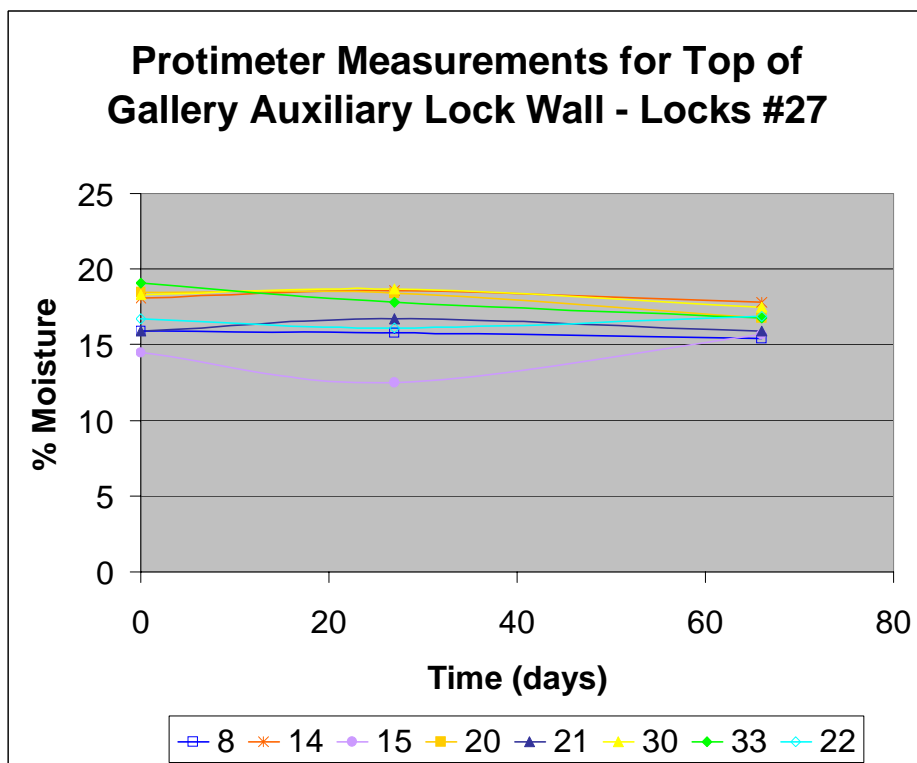


Figure 40. Graph of protimeter values at wall/ceiling juncture of gallery west wall.

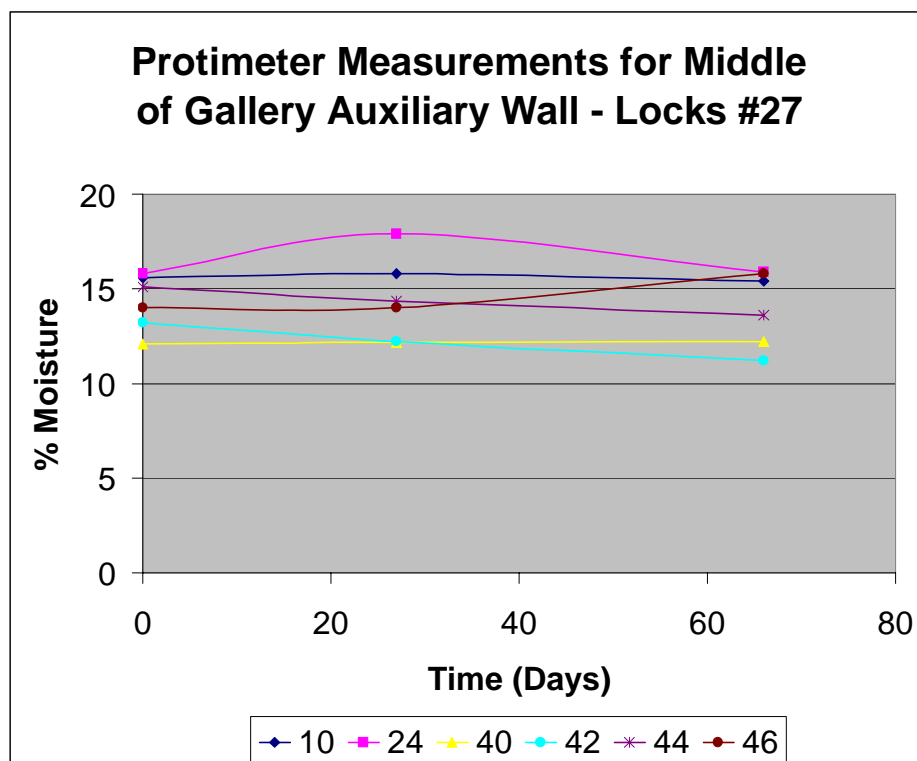


Figure 41. Graph of protimeter values on gallery west wall.

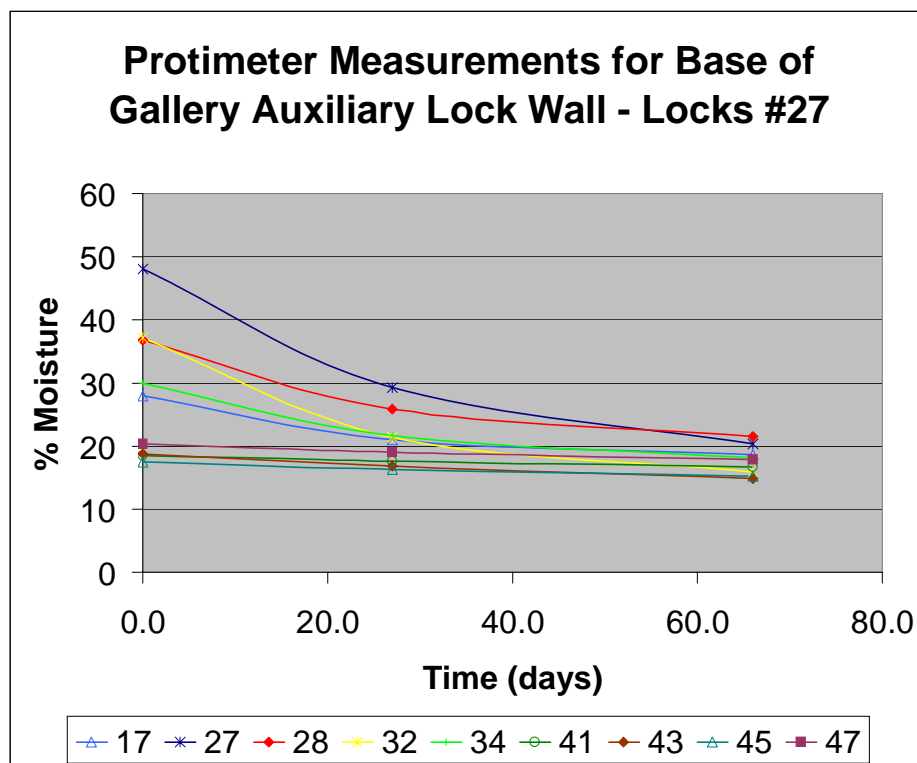


Figure 42. Graph of protimeter values at floor/ceiling juncture of gallery west wall.

During an inspection visit on 4 September 2004, brown streaking was noticed in the grout embedding the wire anodes at the following locations: locations 2 and 4 near the middle of the west wall ceiling section, locations 5 and 6 at the same location but at the floor, locations 8 and 10 at the construction joint east wall at the ceiling and wall, location 21 at the ceiling of the east wall of the northern construction joint, location 33 at the ceiling of the south end of the demonstration section, and, at location 35, the floor at the south end of the demonstration section. This brown streaking possibly indicates acidification in the grout. This acidification results from high current density at the anode and typically occurs at voids in the grout that fill with water. The direct current dissociates and ionizes the water molecules, forming acid at the anode surface. This acid, in turn, attacks the mixed metal oxide coating on the anode eroding it, creating hydrogen gas. Further investigation is needed and, if indeed acidification is occurring, the anode wire replaced.

5 Discussion

Laboratory tests indicate that, for a 4-in.-thick concrete wall, the water permeation is relatively constant. Figures 14–16 show a straight line from the time the test began to the time the EOP system was activated for heads of 15 ft, 20 ft, and 30 ft, respectively. Once the EOP system was activated, the moisture content at the different depths in the concrete decreased at a steady rate for the 15-ft and 20-ft heads. The 30-ft head remained fairly constant. This is an indication that the EOP system could maintain constant moisture content but not decrease it at that head force. At a 25-ft head, the moisture content of the concrete decreased to a point and then leveled off again, maintaining a constant moisture level at that head force.

These experiments did not show the effect of concrete thickness on the point where EOP is unable to effect further drying of the concrete. It appears that 20–25 ft is the maximum head that EOP will effectively dry and maintain at a low level of moisture in a 4-in.-thick wall. At 30 ft, EOP prevents water seepage through a 4-in. thick section, but does not dry the concrete.

The field demonstrations showed the effectiveness of EOP in drying thick concrete walls. Current demand is an indicator of the effectiveness of the EOP system. The higher the current demand, the wetter the concrete in the wall is. Lower current demand is an indicator of drying, because the moisture in the concrete provides the conductivity between the anodes and cathodes.

Figure 27 showed the current demand over time for each of the cathodes installed in the system. Cathode 10, the copper plate cathode in the lock, initially had a relatively high current demand but, once the EOP system was activated, decreased to the same level as all the other cathodes. Cathode 3, the probe cathode near the lock wall surface, began at the same level of current demand as the other cathodes along the wall but increased when the rain was high and the floor was flooded. All the other cathodes showed a drop in current demand.

The effectiveness of the manufactured probe cathodes and the fabricated probe cathodes showed no notable difference. The surface area is the same for both, and the current demand is very similar for both.

The wire anode appears to be more efficient than the probe anodes. The current demand shows a greater decrease with the wire than with the probe anodes (Figure 29).

Figure 31 showed the surface moisture of the lock wall over time. It showed that, even with 4 in. of water covering the floor of the basement, the wall is dryer than when the system was turned on, especially at location 5.

In the gallery at Lock 27, the current demand of the EOP system has reduced and has achieved an equilibrium state. Moisture readings on the main lock and auxiliary lock walls show an overall reduction in current demand at the floor level. This was visible in the gallery since the wet floor had dried out. The tops and middle of the walls have not varied much over time.

6 Conclusions and Recommendations

Conclusions

- Laboratory testing indicates that EOP is able to dry walls of concrete structures to the 25-ft head pressure through a 4-in. wall section.
- Field testing corroborates the laboratory tests showing EOP can dry the concrete in lock house basements and lock galleries that experienced up to 30 feet of head pressure.
- The plate cathodes mounted in the water on the lock walls are effective cathode placements.
- Probe cathodes are also effective embedded in the lock walls.
- The effectiveness of probe cathodes is based on the surface area and not the manufacturing techniques used.

Recommendations

The following recommendations are based on laboratory testing and field demonstrations using EOP to stop water intrusion:

- Testing shows that EOP is able to counter up to 30 ft of head through a 4-in.-thick slab of concrete. The effect of concrete cross-section thickness needs to be investigated to determine how it affects the head resistance capability of EOP.
- When the EOP design includes cathodes placed in nearby water, such as in locks, limit the cathodes to one cathode plate. Water is such a good conductor that only one was needed at Lock 27.
- The EOP system performance should continue by monitoring current levels and protimeter data to develop long-term performance histories for Civil Works structures.

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Appendix: Experimental Procedure for EO Test Specimen Preparation

The concrete test specimens used in this experiment are composed of a uniform mix of Type I Portland cement, fly ash (Pozzolan), coarse aggregate (natural gravel), fine aggregate (natural concrete sand), and tap water. A computer program developed by the National Institute of Standards and Technology (NIST) was used to calculate the exact amounts of each type of material by weight that should be used to achieve the desired mix of concrete. With the quantity of the material specified, the concrete was mixed using a small concrete mixer in accordance with American Society for Testing and Materials (ASTM) standard C192/C192M-98. After the batch had been sufficiently mixed, nine standard test cylinders were poured in accordance with ASTM standard C31.

Once the cylinders were prepared, they were allowed to cure in open air for 24 hours. After that, they were placed in a tank of room temperature water where they remained for the rest of their 28-day curing time. Once the curing was complete, the specimens were removed from the tank of water and stored for later experimental use.

Aggregate Characterization

The *Bulk Specific Gravity SSD* (Saturated Surface Dry) test and the *Absorption Capacity* test for aggregate were performed, and a number was established for each. To determine the specific gravity of the aggregate, a sample of aggregate was soaked in water for 24 hours. This ensured that the sample was saturated. The sample was then removed from the water and towed dry to remove any excess water from the surface. This towel drying removed the glossy appearance of the aggregate, but did not dry it enough to give it a powdery dry look. The aggregate is said to be at SSD condition at this point.

Once that condition was established, 1000 g of the aggregate at SSD was weighed out and the weight recorded. This 1000 g of aggregate was then weighed in water. An electric scale that had an opening in the bottom and a small hook from which objects to be weighed could be hung, was used for this

measurement. The scale was set on a small table with a hole in the middle of it large enough to allow a wire to be attached to the hook in the bottom of the scale, but small enough to ensure that the scale would not fall through. A 5-gallon bucket was placed under the table and filled one-half to three-quarters full of water. A small basket made of fine wire mesh that would let water pass through it easily, but would not let the aggregate pass through, was hung from the hook in the bottom of the scale. The basket was submerged in the bucket of water, and the scale was zeroed. The 1000-g sample was then placed into the small basket and the basket placed back into the bucket and submerged in water. The weight of the aggregate in water was recorded. The aggregate was then removed from the basket in the water and placed in another container for oven drying. The aggregate was dried for 24 hours in an oven at 105 degrees Celsius (°C). The sample was then removed from the oven after drying and the weight of the dry sample was taken and recorded.

To calculate the Bulk Specific Gravity SSD of the aggregate, the weight of the SSD sample in air (B) is divided by the difference between the weight of the SSD sample in air and the weight of the SSD sample in water (C).

$$\text{Bulk Specific Gravity} = \frac{B}{(B - C)} \quad \text{Eq A1}$$

To calculate the absorption of the aggregate in percent, the difference between the weight of the SSD sample in air (B) and the weight of the oven-dry sample in air (A) is divided by the weight of the oven-dry sample in air. That quantity is then multiplied by 100 to yield the percent.

$$\text{Absorption (\%)} = \frac{(B - A)}{B} \times 100 \% \quad \text{Eq A2}$$

The *Total Evaporable Moisture Content* for an aggregate was measured by weighing a sample of stock aggregate in air, then weighing it again after oven drying it. Again, 1000 g of the stock aggregate was weighed, recorded, and then placed in a drying oven at 105 °C for 24 hours. After the sample was dried, it was weighed again and the weight was recorded.

To calculate the Total Evaporable Moisture Content of the aggregate (p), the difference between the weight of the stock sample in air (W) and the weight of the oven dried sample in air (D) is divided by the weight of the oven-dried sample in air. That quantity is then multiplied by 100 to yield a percent.

$$\text{Total Evaporable Moisture Content (\%)} = 100\% \times \frac{(W - D)}{D} \quad \text{Eq A3}$$

Sand Characterization

The *Bulk Specific Gravity SSD* test and the *Absorption Capacity* test for sand were also performed, and a number was established for each. To determine the specific gravity of the sand, a sample of sand was soaked in water for 24 hours. This ensured that the sample was saturated. The sample was then removed from the water and allowed to air dry for several hours by spreading out a thin layer of the sand on a smooth, clean surface. An electric fan was used to move air over the wet sample of sand to decrease the drying time. A special cone for this test was used to establish when the sand was SSD. The sand was placed in the cone and lightly tamped to ensure some compaction. Once the cone was filled with the lightly compacted sand, the cone was removed. If the sand retained the shape of the cone, it was too wet and needed to be dried longer. If the sand slumped off the outside of the cone, but a small pointed peak approximately the same height as the original cone remained sticking out of the slumped sand pile, the sample was at SSD condition. If the whole cone of sand slumped into a pile and no peak stood out, the sand was too dry and a new sample from the soaked material needed to be dried to get the sand to SSD. Once SSD is established, the test must begin promptly since the sand will become too dry within about 5 minutes.

A 500-g sample of the SSD sand was weighed and that weight recorded. A mason jar was then overfilled with water and a small glass plate was used to strike off the surface water at the opening of the mason jar. This served two purposes: (1) to remove any air bubbles that might be collected at the mouth of the jar, and (2) to ensure that the same volume is measured each time the jar is filled. The jar full of water, with the glass plate covering the mouth of the jar, was then weighed and that weight recorded. About half of the water was removed from the jar, and the 500-g sample of SSD sand was poured carefully into the jar. The jar was then filled the remainder of the way with water, and the surface was struck with the glass plate, taking care to remove all the bubbles at the mouth of the jar. The jar full of sand and water was then weighed, and that weight recorded. The water was then poured off the sand, taking care not to lose any sand from the jar, and then the jar was placed in the drying oven at 105 °C for 24 hours. After the sample was dried, it was weighed again, and the weight was recorded.

To calculate the Bulk Specific Gravity SSD of the sand, the weight of the SSD sample in air (S) is divided by the sum of the weight of the jar filled with water (B) and the weight of the SSD sample in air minus the weight of the jar full of sand and water (C):

$$\text{Bulk Specific Gravity SSD} = \frac{S}{(B + S - C)} \quad \text{Eq A4}$$

To calculate the absorption of the sand in percent, the difference between the weight of the SSD sample in air (S) and the weight of the oven-dried sample (A) is divided by the weight of the oven-dried sample. That quantity is then multiplied by 100 to yield a percent.

$$\text{Absorption (\%)} = 100\% \times \frac{(S - A)}{A} \quad \text{Eq A5}$$

The Total Evaporable Moisture Content for sand was measured by weighing a sample of stock sand in air, then oven drying it and weighing that. Again, 500 g of the stock sand was weighed and recorded. Then that sample was placed in a drying oven at 105 °C for 24 hours. After which, it was weighed and the weight recorded.

To calculate the Total Evaporable Moisture Content of the sand (p), the difference between the weight of the stock sample in air (W) and the weight of the oven dried sample in air (D) is divided by the weight of the oven-dried sample in air. That quantity is then multiplied by 100 to yield a percent.

$$\text{Total Evaporable Moisture Content (\%)} = 100\% \times \frac{(W - D)}{D}$$

Concrete Mix Design

A computer program from NIST was used to calculate the amounts of each material to be put into the mix to yield desired concrete water to cement ratio (w/c). The program was accessed on line over the World Wide Web at <http://ciks.cbt.nist.gov/bentz/welcome.html>.

The “Computer Integrated Knowledge System for High Performance Concrete” offers a choice of several programs. The user simply logs on to the web page and chooses the units (in.-lb were used) for the calculations to use. This study used

the “Ordinary Strength Concrete Mixture Proportioning” program from the American Concrete Institute (ACI 211.1-91). This program required input of several pieces of information to calculate the quantities of sand, aggregate, cement, water, etc. to be put into the mix. Once these inputs were entered, the form was submitted and the program yielded the necessary information. The batch mix used to make the concrete test cylinders is shown in Table A1.

Making the Mix and Pouring the Specimens

The program’s output specified the necessary amounts of sand, aggregate, cement and water, which were weighed out and added to that of the mixer. The aggregate was added first, then sand, cement, and lastly water in accordance with ASTM Standard C192/C192M–98. The dry ingredients were mixed together first and small amounts of water were added incrementally, until all of the required water had been added. After it had mixed for approximately 5 minutes, uniform consistency was reached and the concrete was poured into the cylinders. The cylinders were sprayed with a light coat of WD40 prior to the pouring. This was done to aide in the de-molding process once the specimens were ready to be removed from their cylinders. The concrete was poured in three layers and rodded approximately 25 to 30 times to remove any air pockets and to ensure homogeneity throughout the specimen. The exterior faces of the molds were also knocked on to ensure good contact between the cylinder and the concrete. This helped to ensure that the faces of the specimen in contact with the cylinder would have a smooth finish.

Table A1. Concrete mixture proportions for test cylinders.

Job Name:		Mixture CONCRETE MIXTURE PROPORTIONS		Date: 28 June 2002			
Job No.	Mixture Ser. No. Stan Woodson 227 SW 3K@28-5			Chemical Admixture: Ser # % water 80 Dosage, ml/100kg Source: 0			
Portland Cement Type: I Ser No. Source: Lone Star				Pozzolan: Class F Source: Monex		Chemical Admixture: Ser # % water 70 Dosage, ml/100kg Source: 0	
Coarse Aggregate				Chemical Admixture: Ser #			
Type: Natural Gravel, 3/8 in. max Ser.# Source: MS Materials, Vicksburg, MS				% water 80 Dosage, ml/100kg Source: 0			
Fine Aggregate				Air-entraining admixture			
Type: Natural Concrete Sand Ser.# Source: Gifford-Hill, Delight, AR		Serial		Dosage, ml/100kg			
		Source:		0			
Materials							
Material	Size Range	Bulk Spec. Gravity	Unit Wt. lb/cu. Ft		Absorption Percent	Total Moist. Cont. %	Net Moist. Cont. %
Cement		3.15	3150.00				
Fly Ash		2.21	2210.00		May-02		
Fine Aggr.		2.6	2600.00		1.00	1.95	0.95
Coarse Aggr.	3/8"	2.49	2490.00		3.80	0.76	-3.04
Coarse Aggr.			0.00				
Water			1000.00				
3M Fibers		0.91	910.00				
Design Proportions 3.5 cu. ft.							
Total	Material	Solid Volume cu.m./batch	SSD Batch Mass (kg)		SSD Batch Wt. (lb)	Water Corr. (lb)	Actual Batch Wt (lb)
	Cement	0.0693	218		47.7		47.7
	Fly Ash	0.0231	51		11.2		11.2
	Fine Aggr.	0.3391	882		192.7	-1.8	194.5
	Coarse Aggr.	0.3824	952		208.1	6.1	201.9
		0.0000	0		0.0	0.0	0.0
			0.00	L			0 ml
			0.00	L			0 ml
			0.00	L			0 ml
			0.00	L			0.0 ml
		0.0000	0		0.0		0.000
	Water	0.1660	166		36.3	4.3	40.6
Air	0.020		batch water adjusted for water in WRA			40.6	
Air Free	0.980						
Total	Yield	1.000	2269				
w/c =		F/C= %	25	A/CA= %	100	MC= cu m	0.6176
w/c+m	0.57	S/A= %	47			P/M=	0.45
Slump mm		Air Content% (grav)		100.0	Yield, cu m		#DIV/0!
@ 40min		Air Content% (grav) @ 40		100.0	Yield, cu m @ 30 min.		#DIV/0!
Th UW kcm	2316	Air Content% (press)			Temperature, F		
Act UW kcm		Air Content(F)% @ 40min			Temperature, F @ 40		
Act UW kcm					Amv. Temperature, F		

Curing the Specimens

After the specimens had been poured, they were set aside for the weekend to allow the concrete to set. Once the concrete had set, the specimens and test cylinders were placed into plastic 32-gal garbage cans, which were then filled with water. This provided a saturated curing environment. The concrete was kept under water for the remainder of the 28-day curing period.

Dates of Pouring, Placing in Water, and Test Cylinder Breaking

The specimens were poured on Friday, June 28, 2002. They were removed from their cylinders on Monday, June 30, 2002 and placed in the 32-gal plastic garbage cans, which were filled with water. They stayed in the water for the remainder of the curing period. They were removed from the water on Monday, July 29, 2002.

Test Cell Preparation

To test the effect of EOP technology on concrete, the concrete cylinders had to *fit into a test cell that could be installed into the experimental apparatus. To create a test cell, the concrete cylinders were cut into 4-in. tall specimens. Once cut to size, the concrete cores were installed into a polyvinyl chloride (PVC) pipe with flanges on either end. The core was held in place by one coat of E6000 medium viscosity epoxy, layered under one coat of E6100 high viscosity epoxy. This effectively kept the core from shearing and prevented water from transferring between the PVC-concrete interface.

With the concrete core in place, vertical holes were drilled in the concrete face in order to install probes. This was done with a normal drill bit of appropriate diameter. Four holes were drilled at the corners of a square centered on the middle of the specimen face. The holes in two opposing corners were drilled to depths of one-third of the axial specimen length (1-1/3 in.) and two-thirds of the axial specimen length (2-2/3 in.).

After the holes had been drilled, the test cell was sealed off on both faces from any water that would transfer along any gaps in the PVC-concrete interface or through the PVC itself. This was done using the E6100 high viscosity epoxy, which was applied in a thick coat along the inner face of the PVC pipe from concrete face to the outer edge of the PVC, and approximately 1 in. onto the concrete

face itself. After the E6100 coat had time to set, a coat of E6000 medium viscosity was applied over the E6100 coat in order to fill in any gaps that may have formed during curing. The holes were drilled before the epoxy was placed, so the vibrations from the drill would not otherwise damage the epoxy matrix, creating unwanted voids and cracks.

After 3 days the epoxy was sufficiently set to begin probe and anode installation. The probes consisted of stiff copper wire covered in an insulated heat shrink rubber. The anode consists of a malleable zinc plate.

Once the anode and probes were prepared, they were installed into the test cell with grout. The grout mix itself consisted of a 75:25:50 ratio of Portland cement:sand:water. The probes were grouted securely into place so that the sharp point was in good contact with the concrete at the bottom of the predrilled hole (a slight tap with a hammer can improve contact.) The anode was grouted securely onto the concrete face so that there was a sufficient layer of grout between the concrete and anode and also a sufficient layer of grout covering the anode. The grouted-in-place anode had a measured surface area of 5.50 sq in. in contact with the test cell. After grouting was complete, 2 days were allowed for curing.

With everything grouted in place, a final coat of E6100 high viscosity epoxy was applied to both sides of the test cell. This final coat of epoxy was allowed one week to set up, and the test cell was ready for testing.

Test Cell Installation

Once the epoxy in the test cells had time to set, the cells could be installed onto the experimental apparatus. A rubber gasket coated with silicon was placed between the test cell flange and experimental apparatus flange. This provided a watertight lock between flanges. The test cell was then held securely in place with eight bolts that were tightened to a degree that would not warp the PVC flange. Once secured, the silicon was given 2 hours to set. At the concrete face, a wire was secured to the bent portion of the anode, creating a circuit between the cathode, anode, NaCl solution, and the voltage source.

